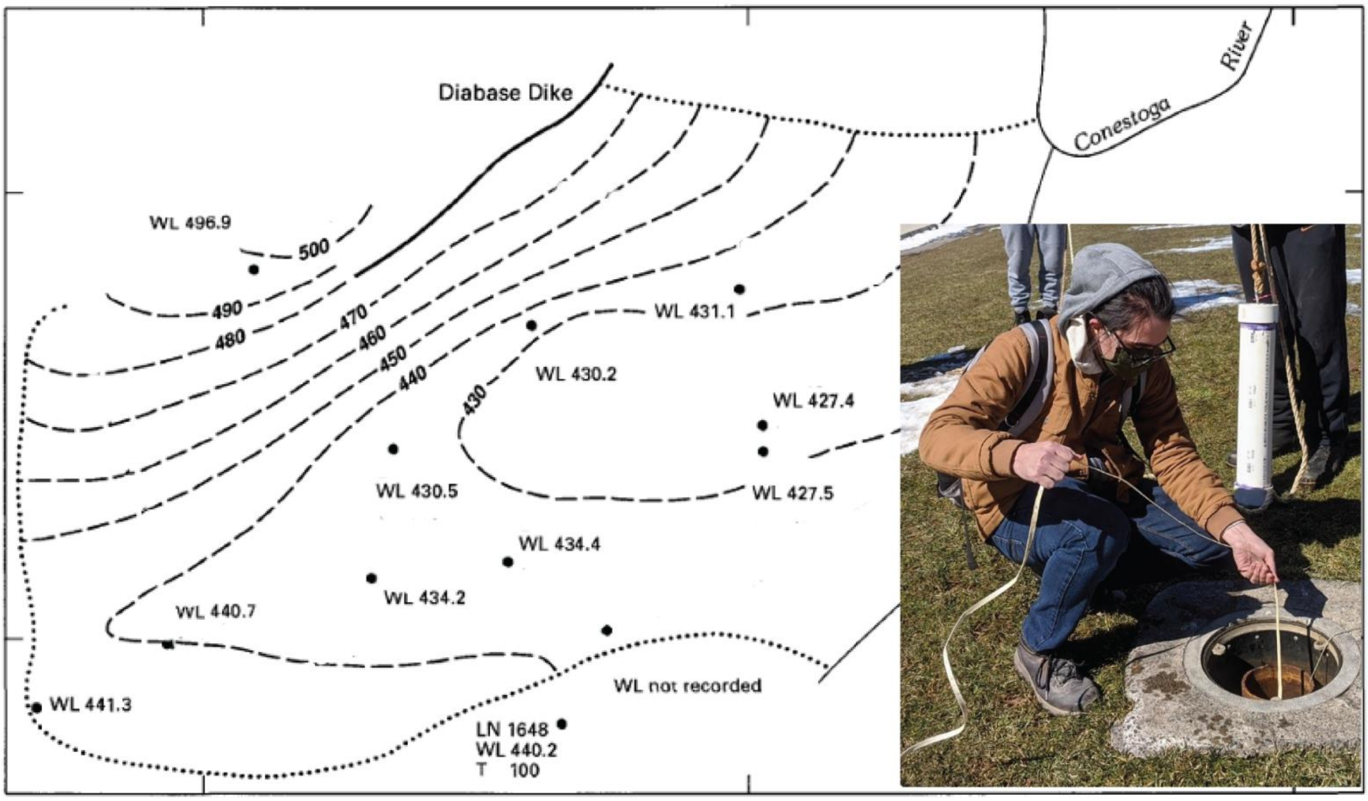

Using Groundwater Head Maps

Laura Toran

THE GROUNDWATER PROJECT

Using Groundwater Head Maps

The Groundwater Project

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Using Groundwater Head Maps

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THE GROUNDWATER PROJECT

Cover Image: Groundwater head map and measuring water level in a well. Map from Lietman, P.L., 1997; photo by Laura Toran.

Dedication

To the students in my Temple University groundwater hydrology classes who tested these exercises. Also, to the hydrologists of the United States Geological Survey (USGS) who made most of the illustrative maps provided in this book; their hard work is invaluable to understanding groundwater flow.

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The Groundwater Project Foreword

The United Nations (UN)-Water Summit on Groundwater, held from 7 to 8 December 2022, at the UNESCO headquarters in Paris, France, concluded with a call for governments and other stakeholders to scale up their efforts to better manage groundwater. The intent of the call to action was to inform relevant discussions at the UN 2023 Water Conference held from 22 to 24 March 2023 at the UN headquarters in New York City. One of the required actions is *strengthening human and institutional capacity*, for which groundwater education is fundamental.

The UN-Water website↗ states that *more than three billion people worldwide depend on water that crosses national borders*. There are 592 transboundary aquifers, yet most do not have an intergovernmental cooperation agreement in place for sharing and managing the aquifer. Moreover, while groundwater plays a key role in global stability and prosperity, it also makes up 99 percent of all liquid freshwater—accordingly, groundwater is at the heart of the freshwater crisis. *Groundwater is an invaluable resource*.

The Groundwater Project (GW-Project), a registered Canadian charity with its beginnings in 2018, pioneers in advancing understanding of groundwater and, thus, enables *building the human capacity for the development and management of groundwater.* The GW-Project is not government funded and relies on donations from individuals, organizations, and companies. The GW-Project creates and publishes high-quality books about *all-things-groundwater* that are scientifically significant and/or relevant to societal and ecological needs. Our books synthesize knowledge, are rigorously peer reviewed and translated into many languages. Groundwater is 'hidden' and, therefore, our books have a strong emphasis on visualizations essential to support the spatial thinking and conceptualization in space and time of processes, problems, and solutions. Based on *our philosophy that high quality groundwater knowledge should be accessible to everyone*, The GW-Project provides all publications for free.

The GW-Project embodies a new type of global educational endeavor made possible by the contributions of a dedicated international group of over 1000 volunteer professionals from a broad range of disciplines, and from 70 countries on six continents. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, youth, undergraduate and graduate students, groundwater professionals, and the general public.

The GW-Project started publishing books in August 2020; by the end of 2024, we have published 55 original books and 77 translations (55 languages). Revised editions of the books are published from time to time. In 2024, interactive groundwater education tools and groundwater videos were added to our website, gw-project.org↗.

We thank our individual and corporate sponsors for their ongoing financial support. Please consider sponsoring the GW-Project so we can continue to publish books free of charge.

The Groundwater Project *Board of Directors*, January 2025

Foreword

Using hydraulic head maps is fundamental to understanding groundwater systems and is a fundamental aspect of professional hydrogeology work. Hydrogeologists are expected to gather water level data and construct contour maps of hydraulic head. At first glance, preparation of a head map would seem to be as simple as using geometric principles to prepare a contour map of topographic elevations from ground surface elevation data. However, positioning of hydraulic head contours requires consideration of factors beyond geometry. These factors incorporate the nature of the groundwater flow system into the development of contours. For example, this includes where recharge and discharge are likely to occur and the general distribution of hydraulic conductivity in the geologic unit represented by the head map. In other words, to construct a hydraulic head contour map one has to think about the hydrologic nature of the landscape and the underlying geology so that the shape and distribution of the contours are consistent with the setting. This thinking is intuitive for an experienced hydrogeologist who accomplishes it without dissecting the problem into its logical pieces. However, for a novice, construction of an acceptable hydraulic head map is commonly a challenging task. Instructors of introductory groundwater courses have hydrogeologic intuition so they are sometimes mystified when students make errors in constructing head maps or cannot deduce information about a flow system from a properly constructed head map. This book is aimed at taking the mystery out of head maps so that students can develop awareness of what must be considered when creating and using head maps and ultimately develop the relevant intuition. The Groundwater Project has published several other books that discuss hydraulic head and the author provides links to these books where appropriate.

Dr. Laura Toran is a professor in the Earth and Environmental Science Department at Temple University, Philadelphia, Pennsylvania, USA. Her experiences with consistent student errors related to head maps over nearly three decades of teaching hydrogeology courses motivated her to prepare this book. A unique feature of this book is its focus on helping people who are new to hydrogeology spot errors in head maps.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, February, 2025

Preface

Al Freeze and John Cherry wrote the textbook, *Groundwater,* that was used in the first hydrology course that I took as a student, and I have used it for many years as an instructor. When I found out that John Cherry wanted to create an open-source revision that would have regular updates, I was excited about finding a way to be a part of the project. Over the past three decades, I created several exercises to help my students understand groundwater head and flow maps. I decided to share these exercises and provide background material to help readers understand how groundwater maps are made. One aspect I try to introduce to my students and in this book is how to spot errors—we are not often shown the wrong way to do something as a tool for understanding the right way. I have seen some of the errors in student assignments as they are trying to learn about groundwater, but also in reports from professionals who are hurried or have not taken the time to really understand groundwater mapping. I anticipate that these exercises and lessons will lead to a better appreciation of how to make and use groundwater maps to protect groundwater resources.

Acknowledgments

I deeply appreciate the thorough and useful reviews of and contributions to this book by the following individuals:

- Andrew J.B. Cohen, New Jersey Institute of Technology, USA;
- William (Bill) Woessner, Professor Emeritus, University of Montana, USA; and
- Xiaomin Wang, Hydrogeologist, S.S. Papadopulos & Associates, Inc., Canada.

Thank you to Keenan Lee and John McCray of Colorado School of Mines for allowing us to include the Seymour example (Exercise 14) from their lab manual co-authored with C.W. Fetter, which was based on data provided by Stan Davis.

I am grateful for Amanda Sills and the Formatting Team of the Groundwater Project for their oversight and copyediting of this book. I thank Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for reviewing, editing, and producing this book.

1 Purpose and Relationship of this Book to Other Books in the Series

This book continues with the description of hydraulic head—less formally called head—and groundwater flow introduced by Cohen and Cherry (2020) in Conceptual and Visual Understanding of Hydraulic Head and Groundwater Flow (PDF)↗(Online)↗ but with increased emphasis on plan view maps of hydraulic head. All maps of groundwater flow tell a story about where the water is coming from and where it is going in an aquifer (or water bearing unit). However, it is sometimes more difficult to identify recharge (source) areas and discharge areas (sink) in plan view. An improved understanding of these concepts in plan view is important for creating and interpreting head maps and is typically the first stage in producing plume maps that suggest the direction of contaminated groundwater flow. These concepts are the subject of this book.

Several important concepts are introduced briefly here as they are covered in more detail in other Groundwater Project books. Different types of aquifers are defined in Basic Hydrology: An Introduction to the Fundamentals of Groundwater Science, Section 5.2 (PDF)↗ and Conceptual and Visual Understanding of Hydraulic Head and Groundwater Flow, Section 5 (PDF)↗(Online)↗. Briefly, unconfined aquifers have an unsaturated zone above them. Confined aquifers are surrounded by low permeability layers and the water level rises above the bottom of the confining layer. Recharge and discharge are explained by Poeter and others (2020) in Groundwater in Our Water Cycle (PDF)↗(Online)↗ and the concept of groundwater-surface water interaction is introduced. Surface water is an important boundary in head maps, and exchange between surface water and groundwater is discussed in more detail by Woessner (2020) in Groundwater-Surface Water Exchange (PDF)↗(Online)↗. Mathematical descriptions of Darcy's Law and groundwater velocity are provided by Poeter & Hsieh (2020) in Graphical Construction of Groundwater Flow Nets (PDF)↗(Online)↗, Devlin (2020) in Groundwater Velocity (PDF)↗(Online)↗, and Uliana (2025) in Basic Hydrology: An Introduction to the Fundamentals of Groundwater Science (PDF)↗. Groundwater flow is highly dependent on hydrogeologic properties of the media, and as any geologist will tell you, the subsurface is complex. These relationships and the heterogeneity of the subsurface are explored by Woessner and Poeter (2020) in Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow (PDF)↗(Online)↗. This book on understanding groundwater head maps can be read independently of those other books, but the interested reader is encouraged to delve into more detail with these additional readings.

This book is organized into sections with exercises to test the readers' understanding of the concepts. Section 2 covers the relationship between head measurements and head maps and the ways in which well placement influences mapping. Section 3 shows how maps and flow lines tell the story of where water is coming from and going to. The importance of identifying recharge and discharge areas to help fill in missing data and common contour patterns are discussed. In addition, this section includes exercises to help readers avoid common contouring errors. Section 4 illustrates why head maps are the first step in mapping groundwater contamination. A zone of contaminated groundwater is called a plume. More information on plumes is available in the book by Robertson (2021) called Septic System Impact on Groundwater Quality (PDF)↗(Online)↗ and by Post and Simmons (2022) in Variable-Density Groundwater Flow (PDF)↗(Online)↗.

The motivation for this book is the extensive use of groundwater head maps in environmental consulting, sometimes without understanding of the underlying principles and sources of data (Figure 1). One of the first steps in site evaluation is often to look for or produce a groundwater head map. Furthermore, a head map is an introduction to the hidden subsurface movement of groundwater because groundwater flow is driven by the hydraulic gradient. Hydraulic gradient is determined in the direction perpendicular to groundwater head contour lines and is the difference between heads divided by the distance between them. When drawn and interpreted correctly, a groundwater head map helps us understand this important resource.

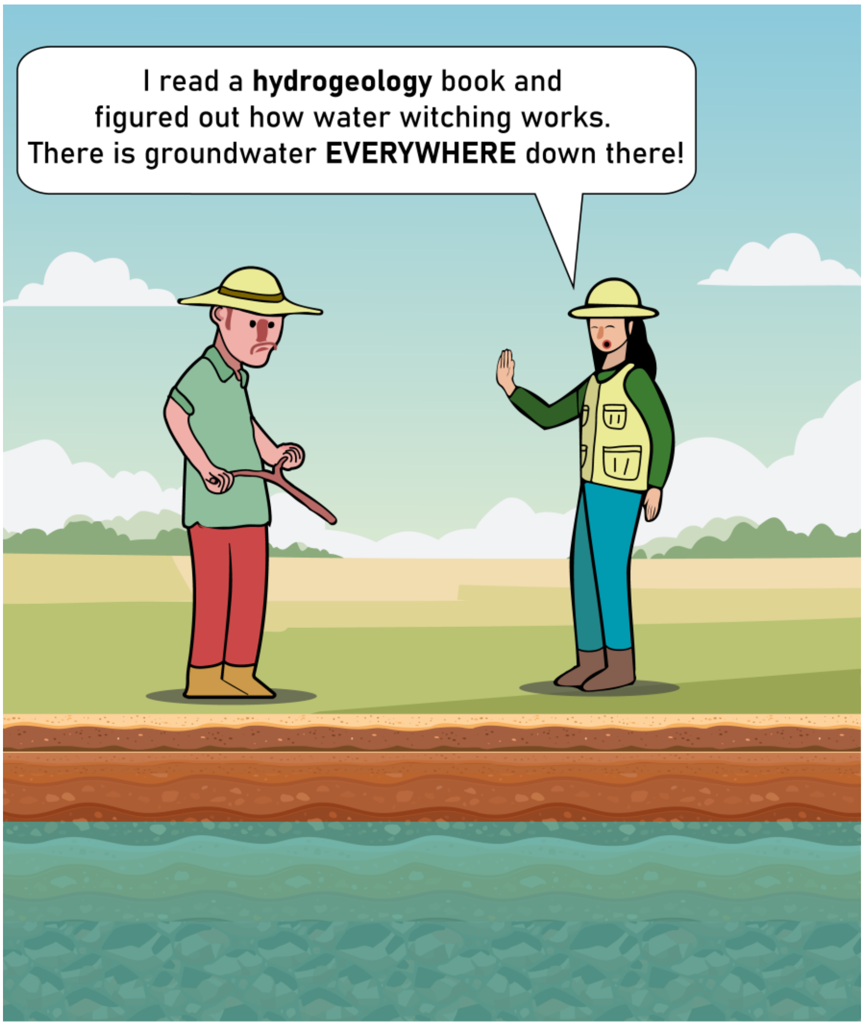


Figure 1 - Water witching explained.

2 Head, Potentiometric Surface, and Flow Lines

2.1 Wells and Head Measurement

A groundwater head map is needed to determine the direction of groundwater movement because flow is driven from high to low heads by the hydraulic gradient which is determined as the difference between heads along a path perpendicular to head contour lines divided by the distance between those heads along that path.

To make a map of groundwater heads, you need to measure head, then put the head value on a map at the well location and draw head contours by connecting values of equal head. Head is typically measured using a well drilled into the ground to allow groundwater to enter and rise to the level of the local groundwater head (Figure 2). Head is the elevation of the water level in a well relative to a datum, typically sea level. It is easy to measure head from the land surface because the land surface also uses sea level as the datum. The head is the elevation of the measuring point minus the depth to water. The measuring point is typically the well casing which can be either above or below ground, so the casing elevation needs to be measured relative to the land surface. A demonstration of depth to water measurement is provided in this video↗ presented by Jesse Dickinson of the US Geological Survey in 2015. Additional sources of head data can be obtained from surface water features as discussed in Section 2.2.

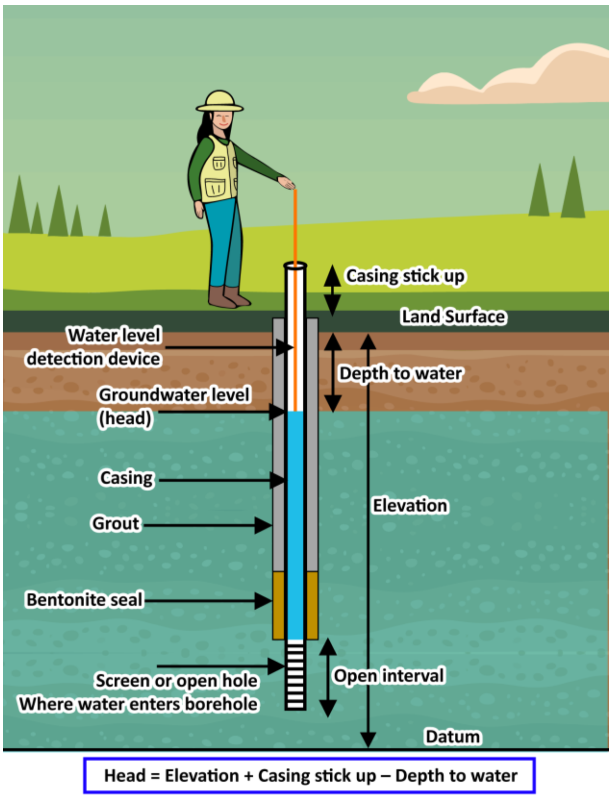


Figure 2 - Water-level monitoring well showing well features and equation for calculating head. There may be a sand pack (not shown) around the screen, but not around an open hole.

Head is the "potential" of the groundwater system; that is, head is the force that controls the direction of groundwater flow from high to low head. When potential gradient is combined with other parameters, the groundwater velocity (rate and direction of flow) can be determined. Understanding head and its measurement is important to making groundwater maps. The energy components of head are described in more detail (with equations) in other Groundwater Project books including Section 4 of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗, Section 2 of Groundwater Velocity↗, and Section 2.2.2 of Basic Hydrology: An Introduction to the Fundamentals of Groundwater Science (PDF)↗.

In addition to making a single measurement of head, continuous recording of head data is useful to understand trends in water levels in wells. Several methods are used to record water level data over time, but pressure transducers are commonly used. A pressure transducer is placed at a known elevation below the water level in a well and measures the combined pressure of the weight of the water column and the weight of the atmosphere that bears down on the water surface. The pressure caused by the atmosphere must be separated from the pressure caused by the water column. Thus, either a separate transducer is used to record barometric pressure, which is subtracted from the pressure transducer reading in the well, or a vent tube that is connected to the land surface is attached to the transducer so that the value recorded is only the pressure caused by the water column above the transducer. Then, knowing the weight of the water per unit length of water column, the pressure is converted to the height of the water column above the transducer. Finally, the height of the water column is added to the elevation of the transducer to calculate the head in the well (i.e., water level with respect to the datum). The recording interval for the transducer is set by the user depending on the expected water-level trends; a shorter interval (minutes) might be used to monitor water level changes in response to pumping while longer intervals could be used for seasonal trends.

The word "well" is sometimes reserved for drilling into aquifers for water supply, so it is important to recognize other terminology related to wells. Piezometer is a term that is sometimes used for a well created specifically to measure head because one component of head is pressure, which is "piezo" in Latin. Generally, people assume the term well refers to a large diameter drillhole and piezometer to small diameter drillholes. This assumption probably arose from the original definition since a large diameter is needed to install pumps and only a small diameter is needed to use a water level measuring device. People may refer to a well that is used to measure head or collect water samples as a "monitoring well" and that is often shortened to "well." These word choices are not strictly applied, and regardless of the word choice, when you are standing at the surface of the earth, and you want to know the groundwater head, you need to drill a hole and install some kind of a well. Drilling methods are discussed by Drage (2022) in Section 3 of Domestic Wells: Introduction and Overview↗.

Well construction influences head measurements (Figure 2). Casing is needed to hold the hole open. This casing can be made of metal (iron typically) or plastic (polyvinyl chloride [PVC] is a common choice). The casing is held in place with grout, except near the bottom of the casing where bentonite clay is used because it swells when wet and forms a tighter seal than grout, which can crack. Grout is less expensive and easier to install, so it is used for most of the well depth. The diameter of the well and the casing depends on what you want to put in the well (e.g., pump, measuring tape), and the cost of constructing the well increases for larger diameters. The depth of the casing depends on several factors, including the geologic material and the purpose of the well. The geologic material affects the depth of the casing because casing is needed through unconsolidated material (loose sediment). The hole would not stay open without casing to prevent loose sediment from falling into and filling the hole. To allow water to flow into a well in unconsolidated material, the casing includes openings (slots or screens). In the USA, screened casing often comes in 5 ft lengths while in Europe it is available in 1- to 3-meter lengths. An open interval with casing screen will be comprised of intervals with an integer number of screen lengths (e.g. 5, 10, 20 feet; 1, 2, 3—or their combinations—meters). Although a drilled hole can remain open without casing in consolidated material (solid rock), there is typically unconsolidated material above it, and the casing needs to extend down from the surface to the first competent layer that will remain open without casing. For a well completed in consolidated rock, this is often where the casing ends. The screen or the open hole below the casing are both referred to as the open interval. An open interval can be any length. The head measurement needs to be associated with the depths of the top and bottom of the open interval. If you did not oversee the well construction, well databases can be a source of information about open interval, although the data quality needs to be carefully evaluated before relying on it. Well data bases are discussed by Kennedy (2022) in the book Water Well Record Databases and their Uses (PDF)↗(Online)↗.

Exercise 1↴ and Exercise 2↴ offer opportunities to evaluate head in a well based on typical field measurements. These exercises reinforce the relationship between depth to water and head as well as the definition of the open interval.

Why is it important to keep track of the open interval? A long open interval may encounter more layers and provide more opportunity for groundwater to flow into a well (Figure 3) thus is an advantage for a water supply well. When measuring head, however, a long open interval is a disadvantage because the water level is a composite of the head in all zones along the interval. If one zone has a substantially higher permeability or larger thickness, the head of that zone will dominate the head measured for the open interval, so data about the character of each layer is needed to understand how it contributes to the head measured in the interval. In Figure 3, both aquifers show groundwater flowing in the same direction (arrows). However, at any given location along the cross section, the shallow aquifer has a higher head than the deep aquifer so a well with an open interval spanning both aquifers has a head between that of the shallow and deep zones. If head from the well with a long open interval were included in a head profile of the shallow aquifer, the profile would have a depression, which would incorrectly reflect groundwater flowing in from both sides perhaps indicating withdrawal of water by a well. If head from the long open interval were used in a head profile of the deep aquifer it would appear as a mound that would incorrectly suggest a local source of recharge with water flowing away in both directions.

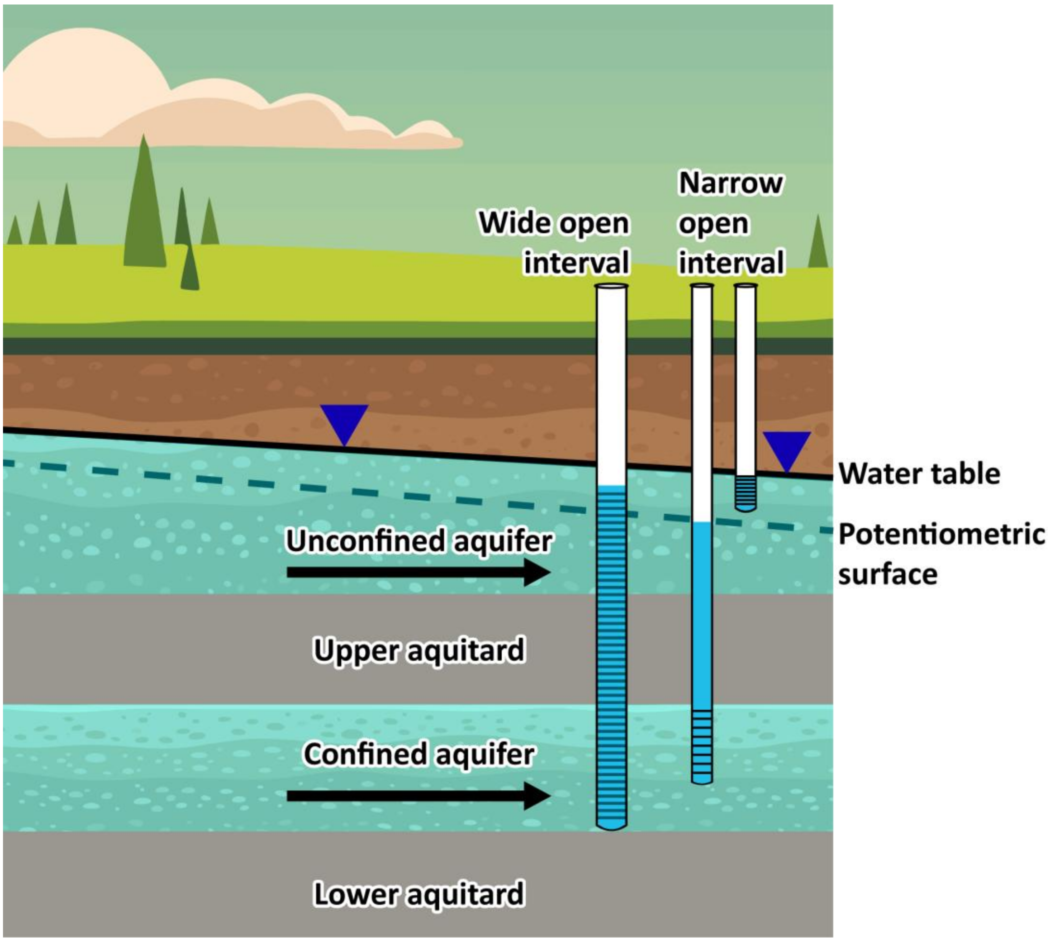


Figure 3 - A well with a long open interval that crosses more than one aquifer will have a head value between the values of the two aquifers. The upper unconfined head is indicated by the water table and the lower confined aquifer head is indicated by the potentiometric surface. The composite water level depends on the head and transmissivity (product of hydraulic conductivity and thickness) of each aquifer. The head from this long open interval cannot be used to map head in either aquifer.

The cross section presented in Figure 3 illustrates two different aquifers, unconfined and confined, with two different water levels. The surface of the unconfined water level is often called the water table, although it is not a flat surface like a table. The water table is the dividing line between the unsaturated zone above and the saturated zone below which is where groundwater is found. The dashed line labeled potentiometric surface is the water level for the confined aquifer. The water level in a confined aquifer is always above the bottom of the confining aquitard. The location of the potentiometric surface reflects the fully saturated conditions of the confined aquifer and the additional head caused by the confining conditions.

Shallow and deep aquifers may have very different flow directions such as near the Love Canal landfill where the shallow unconfined aquifer has heads indicating southward flow toward the landfill and the deep confined aquifer has heads indicating westward flow toward the landfill (Figure 4). Use of heads from open intervals that penetrate both the shallow and deep zone to create a head map of either zone would introduce numerous errors rendering the maps inaccurate. Thus, head measurements from intervals open to multiple aquifers should not be used to create head maps. Water quality sampling is also affected by open intervals that encounter more than one layer because the water sample is a mixture of chemistry from different layers.

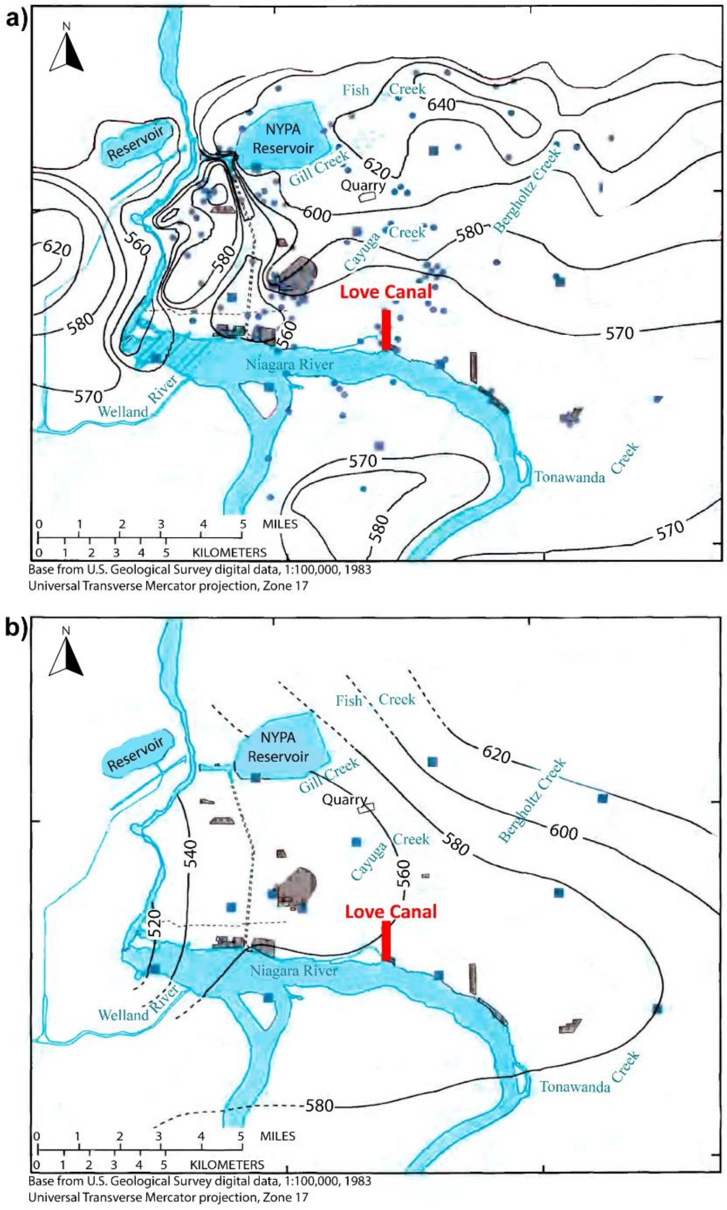


Figure 4 - Head maps of a) the shallow (overburden) and b) deep (dolomite) aquifer in the Niagara Falls area (modified from Yager, 1996). The Love Canal landfill is located along the river. Contours of head are in feet (600 ft ≈ 183 m, and 20 ft ≈ 6 m); and wells are noted as either circles or squares. The contour values are generally lower in the deep aquifer. The direction of flow differs in the two aquifers as determined by envisioning flow to be approximately perpendicular to the contour lines.

In some locales, head values vary with depth within one aquifer. This indicator of vertical flow is commonly observed in recharge and discharge areas (Figure 5). The movement of groundwater from a recharge area to a discharge area defines a groundwater flow system. Recharge areas are where water enters the groundwater flow system (downward flow), and head values are higher in shallow wells and lower in deep wells. Discharge areas are where groundwater exits the flow system (upward flow), and head values are higher in deep wells and lower in shallow wells. To map recharge and discharge areas, "nested wells" are drilled at multiple depths as discussed in Section 3 of Conceptual and Visual Understanding of Hydraulic Head and Groundwater Flow↗. Such "nested wells" are rare because they can be expensive to drill. Head at multiple depths can also be measured using nested piezometers placed in a single borehole provided that they are separated by high integrity seals. Multi-piezometer nests were introduced in a study of the Borden Landfill (Cherry et al., 1983) to provide more detailed contaminant plume mapping both horizontally and vertically.

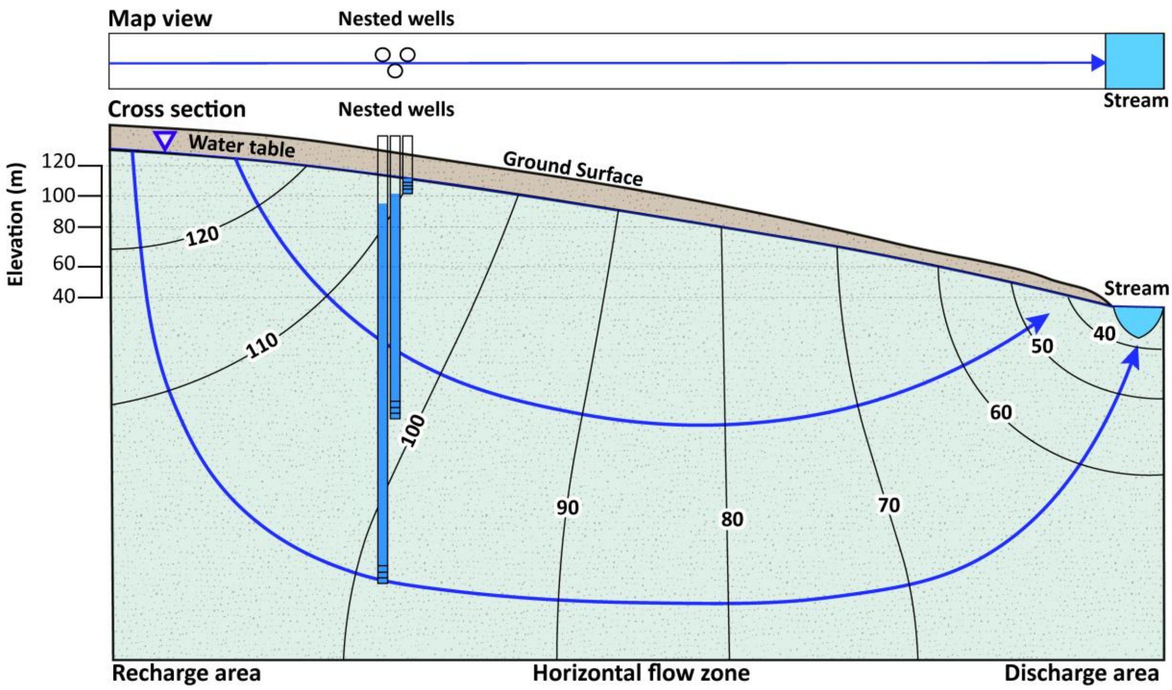


Figure 5 - Illustration of the nature of head contours and flow lines in an unconfined groundwater flow system, illustrating their character in a recharge area, horizontal flow zone, and a discharge area. The nested wells in the recharge area show a decrease in head with depth. The scale bar represents elevation.

Somewhere between the recharge and discharge areas flow direction has to reverse from downward to upward so there is an area of horizontal flow where there is little or no change in head with depth. If recharge is focused in the uplands the zone of horizontal flow may be extensive, whereas if there is substantial contribution to recharge over most of the basin then the horizontal flow zone is small. A large area of many regional aquifers is made up of these horizontal flow zones and, given this infrequency of vertical flow, people sometimes assume all aquifers are only two-dimensional. If wells are completed at only one depth or the wells have long open intervals, the vertical head differences in recharge and discharge areas can easily go unnoticed. However, if you use hydrogeologic principles to identify likely recharge and discharge areas, then you will know which wells are in the horizontal flow zone and useful to include in a head map without worrying about whether they have a short or long open interval. Identification of recharge and discharge areas is covered in more detail in Section 3.

Exercise 3↴ provides the opportunity to estimate and draw head levels in nested wells in the horizontal flow zone and the discharge area. To complete this exercise, it is useful to recognize several features in Figure 5 that help identify the head values. Given that hydraulic pressure is zero at the water table, the hydraulic head is equal to the elevation at the water table. Thus, for example, the 120 m equipotential line intersects the water table at an elevation of 120 m. The water level in the wells rise to the elevation equal to the average head over the length of the well screen. For example, the westernmost well water level of 98 m is the average head over the length of the screened interval. In the discharge area, heads at depth are higher than the elevation of the ground surface. Some groundwater discharges to the stream, then flows downstream as surface water. Groundwater also discharges via transpiration as water is drawn up by plant roots. This is the case where flow lines point to the ground surface in locations where there is no water body. This is not observable as flow on the surface, but might be discerned by noticing the type and density of vegetation along the stream relative to the uplands. In arid areas, groundwater may discharge by direct evaporation from the water table. In an idealized setting, the groundwater system continues to the right in a mirror image of the diagram shown in Figure 5.

In addition to spatial variation of head, there are temporal variations of head. Two important factors that cause temporal changes in head are seasonality and pumping groundwater (Taylor & Alley, 2001). These factors can be evaluated when water levels are measured at multiple points in time.

In seasons when there is little rain, head values will tend to be lower and in seasons where there is a great deal of rain, head values will tend to be higher. There is commonly a lag between wet or dry periods and the associated rise or fall of groundwater levels in wells. When selecting data for creating a head map, it is ideal to use data from the same date. If insufficient data are available from one day, then the period is extended until it includes enough data. Data should be from the same season for all the wells unless the system does not exhibit seasonal variation. In the case when data are not collected on the same date, the hydrogeologist should assess the variability of head in each well with multiple measurements collected over the time period. Wells that do not follow the trends of water levels of most wells in the dataset can be eliminated, or uncertainty can be expressed using error bars on the contours or by producing maps with alternative interpretations of the head contours.

Water levels in pumping wells should not be used to construct head maps because their water levels vary as the pump is turned on and off and they are unlikely to recover to static conditions between pumping. Water levels in nearby wells can also fluctuate as the pump is turned on and off. There are equations that can account for water level changes due to pumping if the aquifer properties are known. This is discussed further by Woessner and others (2023) in An Introduction to Hydraulic Testing in Hydrogeology: Basic Pumping, Slug, and Packer Methods (PDF)↗. Thus, it is important to observe the conditions surrounding the water level observation wells and adjust the timing of the measurements selected for mapping.

Exercise 4↴ provides an opportunity to evaluate variation of head data with time.

2.2 Potentiometric Surface (Head Contours)

The relationship between head contour lines and flow lines is introduced in Section 2.1 and Figure 5 of this book, and in other Groundwater Project books, specifically Conceptual and Visual Understanding of Hydraulic Head and Groundwater Flow (PDF)↗(Online)↗ and Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow (PDF)↗(Online)↗. Head contours are lines that are drawn through points of equal head. Furthermore, water always flows from high head to low head allowing us to draw flow lines on contour maps. Essentially, groundwater flows down the contours of a potentiometric surface, just as surface water flows down the contours of a topographic land surface. The notable difference between groundwater potential contours and topographic contours is that groundwater potential contours fill a three-dimensional space while topographic contours reflect a two-dimensional space. However, a head contour map represents potential within a plane of flow, rendering it a two-dimensional portrayal. In an isotropic system (permeability the same in all directions), flow lines are perpendicular to contour lines. Let's explore the potentiometric surface (i.e., head contour surface) further by examining contours of a head map for Nassau County, New York, USA.

Contours for Nassau County, New York, were drawn using data from 35 and 64 wells for a roughly 220 km^2 area (85 mi^2) at both a high and a low water level (Figure 6). For both maps the contour intervals are 10 ft which is ~3 m (the maps were made by the U.S. Geological Survey so are in English units). The highest value contour is in the north and the lowest in the south toward the bay, so the water is flowing from the north out to the bay which is connected to the Atlantic Ocean, and thus its surface is at sea level. The well close to the 10 ft contour has a water level of 10.5 ft. The well halfway between the 20 and 30 ft contour has a water level of 25 ft. Thus, the spacing of the contours is determined by the head (i.e., the water level) in the wells. Exercise 5↴ uses this information to provide an opportunity to test understanding of concepts related to head contour maps.

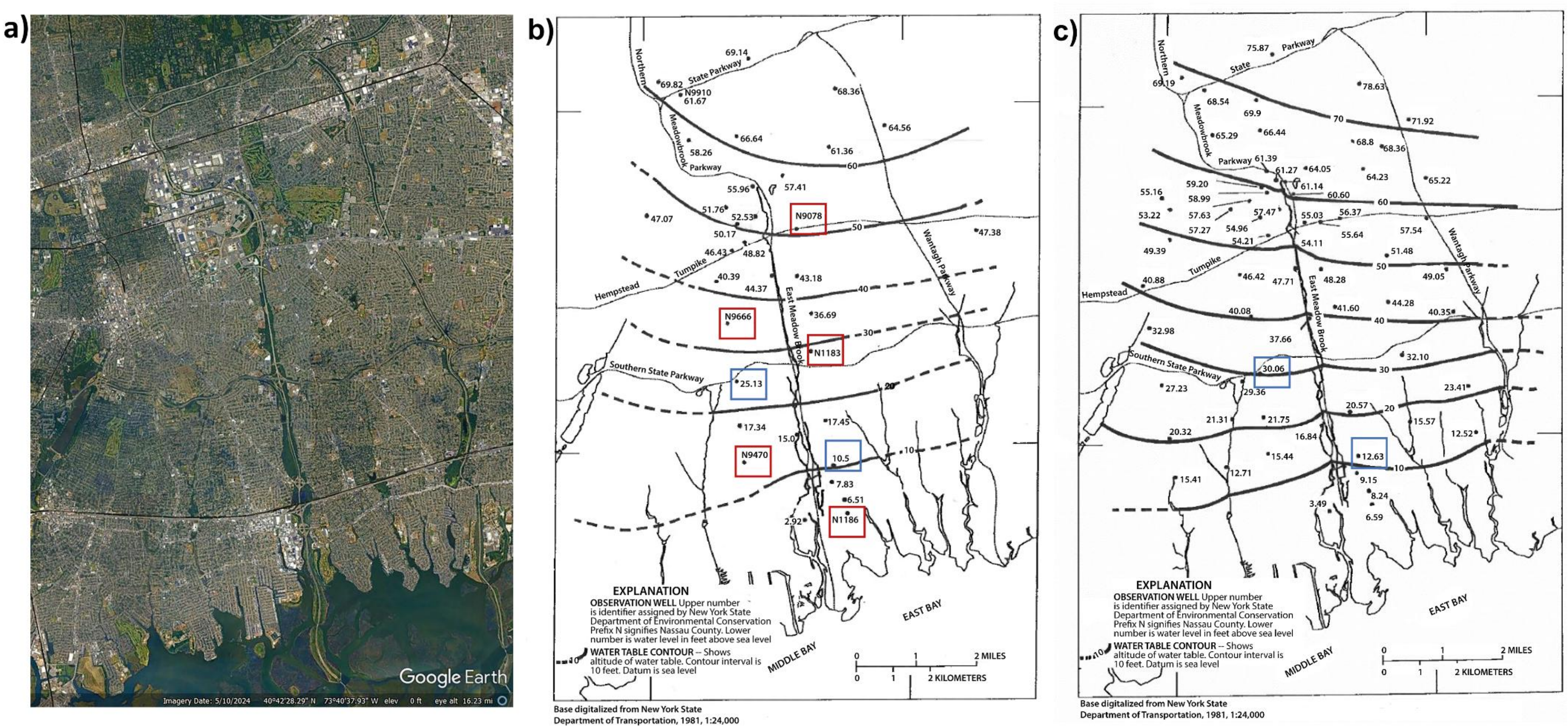


Figure 6 - Groundwater head maps for two different time periods, Nassau County, New York, USA. a) Google Earth photo of the area. b) Head map from data collected between 15 September and 14 October of 1988 showing below average water levels for early autumn. c) Head map from data collected in October 1990 showing above average water levels for early autumn. For both (b) and (c): head data from individual wells (dots) are used to draw the contours and lines are dashed where they are inferred because data are not available. This map is used for Exercise 5↴. The wells indicated using red boxes are missing head values for the 1988 data set. The blue boxes indicate wells that are useful for comparison of the two time periods (panels (b) and (c) are modified from Stumm & Ku, 1997). 70 ft ≈ 21.3 m and 10 ft ≈ 3 m.

To draw contours, we need to interpolate values of head between well locations to estimate where to draw the contours in areas where measurements are not available. At least three measurements are needed to interpolate head because a surface needs to be defined in order to determine the flow direction and two points can only define a line, not a plane. A map of a shopping plaza is shown in Figure 7. It indicates three monitoring wells which were drilled to estimate the groundwater flow direction near a former dry-cleaning business. Dry cleaners are a common source of solvents such as PCE (tehtrachloroethylene) that can contaminate groundwater, although efforts are underway to reduce use of PCE (Ceballos et al., 2021). Water levels shown on the map in Figure 7 vary from 64.69 ft to 61.4 ft above sea level. English units are used here because the US Geological Survey (USGS) basemap is in feet. In order to draw contours, it is useful to select a round number to use as the contour interval (e.g., 1 ft) and determine the number of contour lines that will occur between each pair of wells. Using a 1-foot contour interval, three contours (62, 63, and 64 ft) will occur between the wells with water levels of 61.4 ft and 64.69 ft. There will be contour lines for 62 ft and 63 ft between the wells that have water levels of 61.4 ft and 63.77 ft. Finally, between the wells that have water levels of 63.77 ft and 64.69 ft there is only one contour line for 64 ft. Exercise 6⤵ provides an opportunity to draw contours on the map shown in Figure 7.

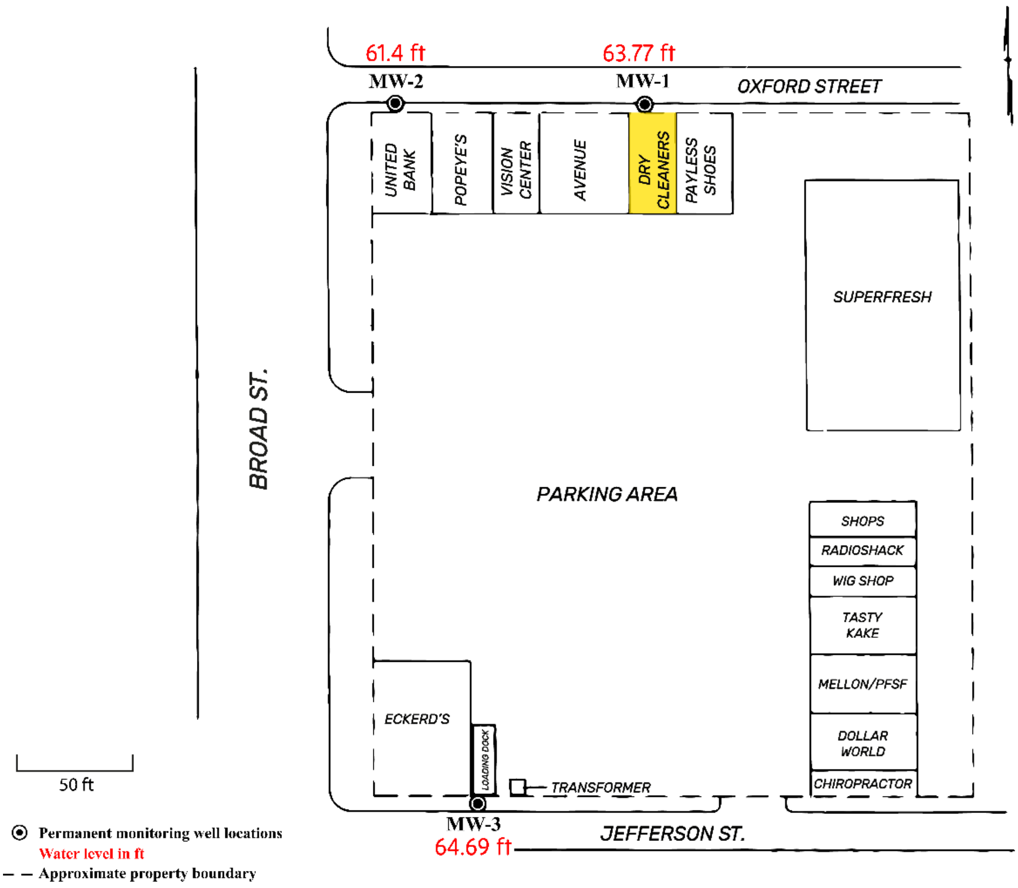


Figure 7 - To look for possible contamination from the Dry Cleaners (yellow highlighted building) in this shopping plaza three wells were drilled to find the groundwater flow direction. 65 ft ≈ 19.8 m and 50 ft ≈ 15.2 m.

Surface water features can be an important component of mapping groundwater heads. The relationship between groundwater and surface water is discussed in more detail in Groundwater-Surface Water Exchange (PDF)↗(Online)↗. These features often indicate groundwater discharge (and occasionally recharge) locations and thus, they provide a measure of the elevation of groundwater head that can be incorporated into the head map. For example, in the Nassau County map (Figure 6), we used sea level as a zero contour. The discharge area in Figure 5 showed a stream which had a head less than 40 m but greater than 30 m. Perennial streams are streams that flow all the time, typically due to groundwater discharge, but they can also receive water inflow from human sources such as wastewater treatment plant discharge. The elevations of the water level in streams at baseflow (i.e., not during storm runoff) indicate the groundwater head at each point along the stream reach. Surface water features thus complement data on groundwater head obtained from wells.

Groundwater head contours will form a V pointing upstream where groundwater discharges to the stream, similar to the V's on topographic maps that indicate overland flow will be funneled to a drainage (Figure 8). Contours need to cross the stream at different elevations to indicate the flow direction of the stream and form a V pointing upstream to indicate groundwater discharge (Figure 9a). Figure 9b is incorrect because the head of a stream decreases along its length, but this map shows the stream elevation as one value indicating that it does not flow. On this incorrect map, contours do not form a V even though groundwater discharges to the stream. If the stream does not slope, there would be nowhere for the discharging groundwater to go except into the atmosphere. In Figure 9c, the groundwater flow lines do not discharge to the stream. Given that the stream is specified as a gaining stream, this map is incorrect. In Figure 9d, the contours form V's pointing downstream. However, for the groundwater flow arrows to show discharge, they point from low to high values instead of high to low values, which is incorrect. The map in Figure 9d could be possible if water is flowing from the stream to groundwater (recharge), but generally such contours are more rounded instead of forming a V. Not all streams are discharge areas. Streams can recharge the groundwater system. These are called losing streams in contrast to streams receiving groundwater discharge, which are called gaining streams. If the water table is connected to the stream, then the stream can be used as a head for a groundwater head map. Some streams are perched, meaning they are not connected to the water table. Perched streams can recharge the groundwater system via downward leakage of water through the unsaturated zone that eventually reaches the water table, but in this case the stream elevation does not reflect the groundwater head elevation. Exercise 7↓ provides an opportunity to map contours with and without a gaining stream.

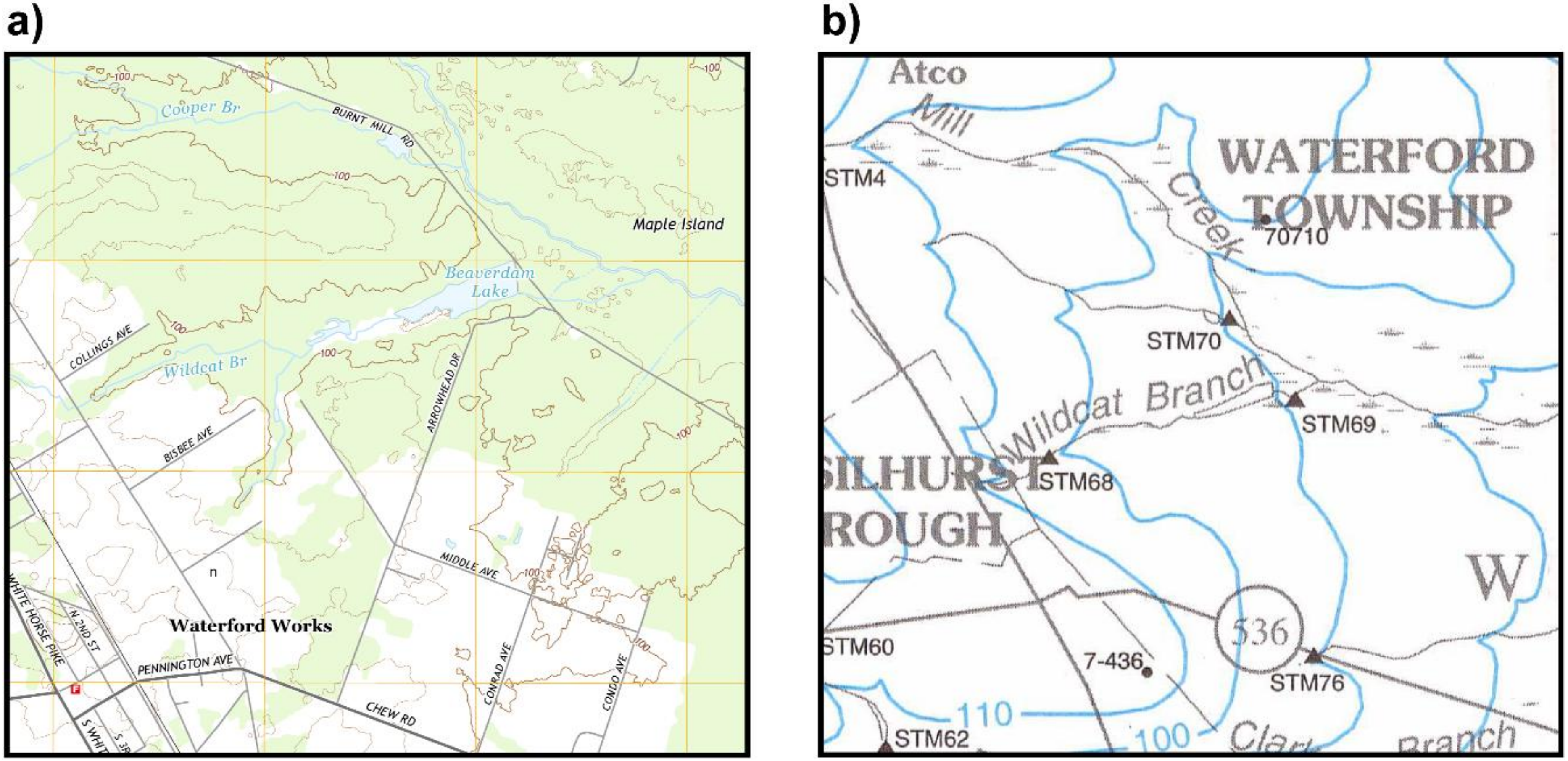


Figure 8 - Maps showing a) topographic contour V's (brown lines) indicating where overland runoff flows to drainages and b) groundwater head contour V's (blue lines) indicating where groundwater is discharging to streams and the stream elevation can be used as a point on a groundwater head map in the Mullica River Basin, Wharton State Forest, New Jersey, USA. The maps are created by the USGS. The topographic map (a) is excerpted from the USGS Hammonton Quadrangle map. The groundwater head map (b) is excerpted from Johnson and Watt (1996). Contours in feet, 100 ft ≈ 30.5 m.

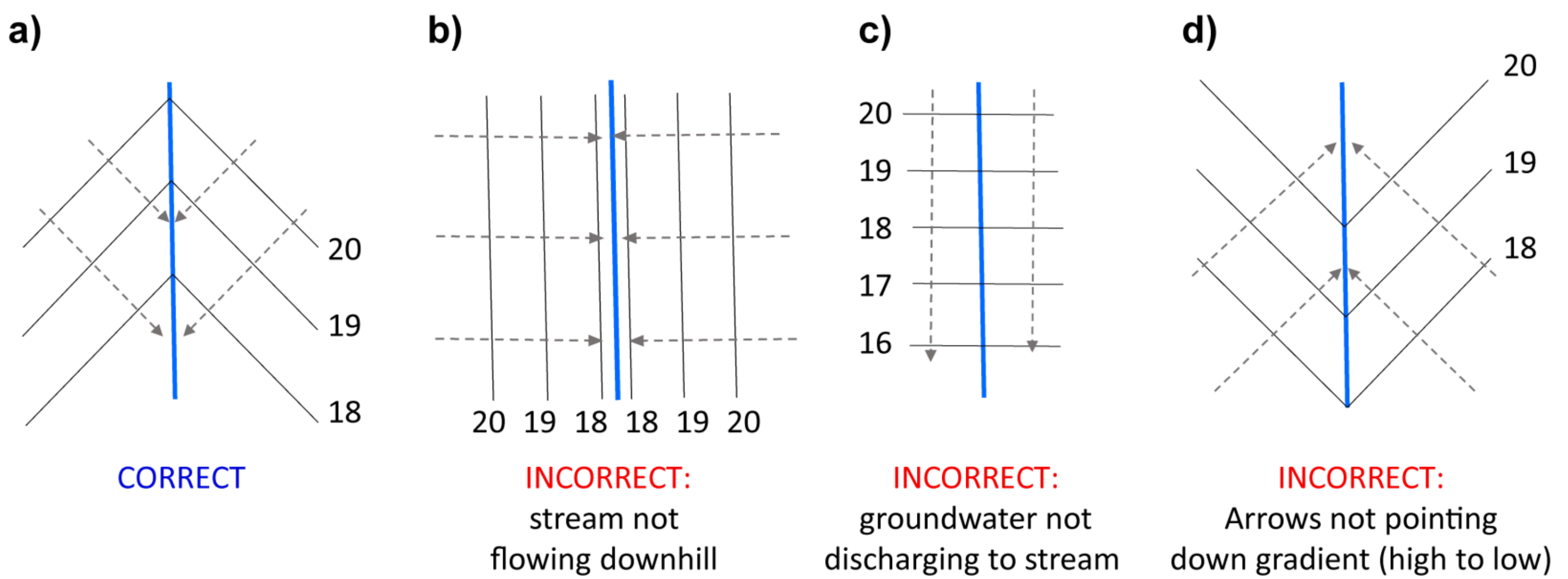


Figure 9 - Sketches of groundwater head maps in plan view showing incorrect and correct relationship between groundwater flow lines and head contour lines around a gaining stream (i.e., a stream receiving groundwater discharge). In these diagrams the streams are flowing from north (top of page) to south. a) A correctly sketched configuration of groundwater head and flow lines around a gaining stream. b) An incorrect sketch because the stream has no elevation change along its length and so is a still body of surface water, not a gaining stream. c) An incorrect sketch of a gaining stream because groundwater flows parallel to the stream and does not discharge to the stream. d) An incorrect sketch of a gaining stream because groundwater head contours V downstream and flow lines are drawn from low to high head whereas groundwater flows from high to low head. Cross-sectional views of groundwater-surface water interaction are shown in Groundwater-Surface Water Exchange (PDF)↗(Online)↗ and in Figure 10 of this book.

Lakes can also be groundwater discharge or recharge areas, but with their greater width, the relationship between groundwater and surface water can be complex (Figure 10). Groundwater can discharge to a lake on all sides (Figure 10a). Lakes that are connected to the water table and have the highest head in an area can be a source of recharge to groundwater (Figure 10b). A lake can be perched above the groundwater table and have no exchange of water with the groundwater system because it has low permeability lakebed sediments and water is lost to evaporation or surface water outflow (Figure 10c). Groundwater can flow in one side of a lake and out the other (Figure 10d). The contours around a lake often are parallel to the boundary of the lake (Figure 10a, b, and d). The cross sections in Figure 10 are also relevant to streams, although flow in one side and out the other (Figure 10d) is not common for streams. Exercise 8↴ illustrates what groundwater maps tell us about the direction of groundwater flow to lakes.

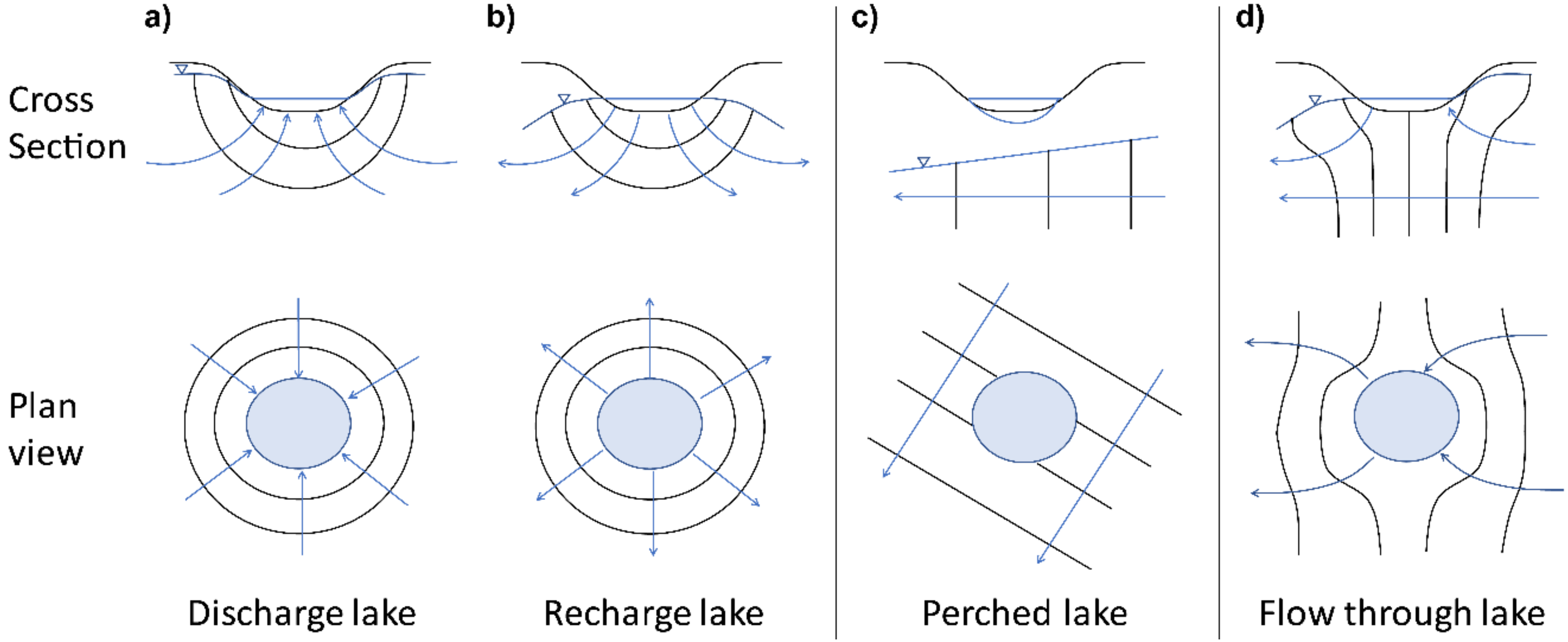


Figure 10 - Relationship between groundwater and lakes, shown in cross section and plan view contours (Modified from Toran, 2019). Sketches of groundwater head contours and flow lines near a) a gaining lake; b) a losing lake; c) a perched lake; and d) a flow-through lake. The cross sections also apply to streams, although flow through (d) is not common in streams.

The head maps from the Love Canal Superfund site near Niagara Falls, New York, USA (Figure 4), illustrate how recharge and discharge can differ for shallow and deep aquifers, with implications for transport of waste in aquifers. Love Canal was a site of an abandoned trench for a canal that was used for waste disposal between 1942 and 1953 (USEPA (n.d.)↗). Because waste disposal was poorly regulated at the time, the land was sold to build a school and homes. A rise in groundwater levels brought the contamination to the surface in the 1970s. A federal and state cleanup was initiated to address the emergency, and 950 families were evacuated. The original polluters were long gone, which led to recognition that legislation was needed to clean up abandoned waste sites. In 1980, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) was passed, which included the Superfund program to provide funds for cleaning up hazardous waste and the Love Canal site was placed on the list of sites. There are two aquifers underlying the waste site. The shallow aquifer is glacial overburden that was contaminated during the unregulated disposal. The deeper aquifer is a dolomite that discharges to the Niagara River, which is a source of drinking water. Groundwater modeling suggests that the aquitard (low permeability formation) between the overburden and the dolomite aquifer provides protection from contamination, but any fractures or penetration of the aquitard is a potential risk (Mercer et al., 1983). Exercise 9↴ examines groundwater maps around Love Canal to understand groundwater flow between shallow and deep aquifers.

There are errors associated with making head measurements, and recognizing the potential errors can help with interpretation of head data when drawing a contour map. The instrument used to measure depth to water can introduce errors, for instance, by using different measuring instruments, or by different people who measure the depth to water taking the measurement at a different reference point on the well. The measured well-casing elevation can also include error. Head map makers need to be aware of potential transient effects that could affect one well but not its neighbor such as pumping. When comparing distant wells or across long periods, difference in climate and/or precipitation events can impact measurements. Using data from different time periods in one map can introduce errors. When such data are used, it is assumed that these errors will be smaller than the head differences being evaluated, but site-specific errors should be accounted for when interpreting head data. The depth of the well and open interval influence which aquifers are being measured. It is up to the hydrogeologist to make sure head maps are based on a single aquifer with essentially horizontal flow. Saines (1981) provides illustrations of erroneous contour maps from mixed aquifers and reverse flow from a stream during a storm event. He recommends starting with shallow wells and a good geologic cross section, then following up with deeper wells to be contoured separately. Furthermore, when computer contouring programs are used to make head maps, errors may be introduced by not accounting for physical features that provide data for head in groundwater systems. The exercises provided in Section 3 of this book are designed to help the reader spot such errors and make sensible maps.

3 Using Potentiometric Surface Maps to Illustrate a Groundwater Flow System

Groundwater potentiometric surface (also called head maps) tell a story about where the groundwater comes from and where it is going (as described in Section 8 of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗ and Section 9 Basic Hydrology: An Introduction to the Fundamentals of Groundwater Science (PDF)↗. This story describes the groundwater flow system including the recharge (entry), flow, and discharge. Not every map will capture both the recharge and the discharge areas, but most maps at least hint at them. Use of the framework for constructing a head map, drawing flow lines, and interpreting the map as presented herein provides a good basis for judging whether a head map is correct. Being able to spot an error in a groundwater head map can prevent misinterpretation. A properly constructed groundwater head map can help protect water resources from over-exploitation (e.g., too much pumping) or contamination (e.g., development of contamination plumes, as discussed in Section 4).

3.1 Common Contour Patterns

Because data are typically limited, a good deal of judgement is required when drawing groundwater head contours and flow lines. Often areas with data gaps need to be filled with likely head contours and flow lines. Some of these gaps can be filled by applying hydrogeologic knowledge and using several common contour patterns. These patterns include recharge, discharge, and horizontal flow (which connect recharge and discharge areas). In the next sections, additional patterns that are less common are discussed: cones of depression from pumping and flow near geologic boundaries. Sometimes head measurements at just a few locations can distinguish these patterns.

3.1.1 Recharge Patterns

Recharge areas are characterized by divergent flow and contours that are roughly concentric with higher head in the center (Figure 11). The contours do not typically form a circle, instead they are usually ovate, often stretching out like a ridge over a long distance. The flow lines look like spokes extending out from a central area. This divergent flow pattern results from infiltration to the aquifer.

In Figure 6, the recharge area is only partially shown, but there is a curve in the northernmost contour that suggests divergent flow. In Figure 4a there are four areas of concentric contours. There are no obvious concentric or curved contours in the lower aquifer in Figure 4b, so the recharge area is not visible on Figure 4b (which is more common for deeper aquifers which may have distant recharge areas). The recharge area for shallow aquifers is often along a topographically high area; as in Figure 5 of this book and in Figure 75 of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗.

The map shown in Figure 11 is from a flat area of Florida, USA, yet it shows a distinct recharge zone. This recharge zone is centered on a tree farm which is indicated by the rectangular outline on the figure and receives extensive irrigation. This irrigation provides recharge to the aquifer.

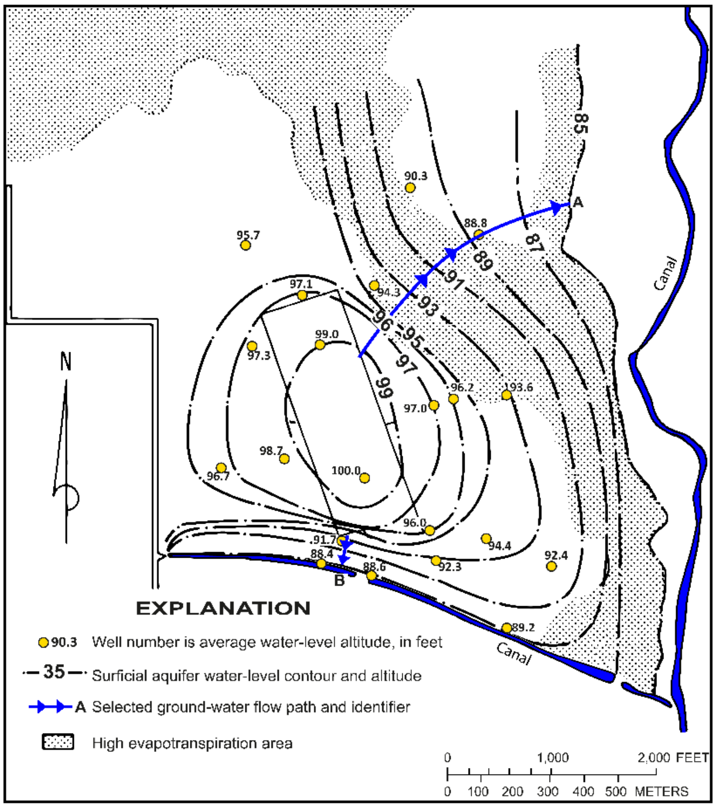


Figure 11 - Example recharge area in the relatively flat terrain of Florida. The rectangular area is a spray irrigation site (Adapted from German, 1990). Contours in feet, 99 ft ≈ 30.2 m and 87 ft ≈ 26.5 m.

3.1.2 Discharge Patterns

Discharge areas are characterized by convergent flow lines and head contours that may mimic the shape of surface water bodies. When contours converge there must be an outlet for the groundwater. The outlet could be a surface water feature, a pumping well, a subsurface drain (which could be manmade or a karst cavern), or withdrawal by plants for transpiration, otherwise the flow lines would reach a "dead end" which is an impossibility.

These convergent flow patterns have different shapes for streams, lakes, and drains. As shown in Figure 8b and Figure 9a, there are V-shaped contours around streams that are discharge zones. There are multiple groundwater discharge areas in the Mullica River basin (Figure 12). The contours form Vs along most of the tributaries of the Mullica River and the contours widen abruptly where groundwater encounters the wetland. There are a limited number of wells to provide data for mapping head, so the V of the contours is inferred based on the known connection between groundwater and surface water in the area. In Figure 11, the discharge areas are canals with shallow gradients, so convergent flow is not discernable using the head contours.

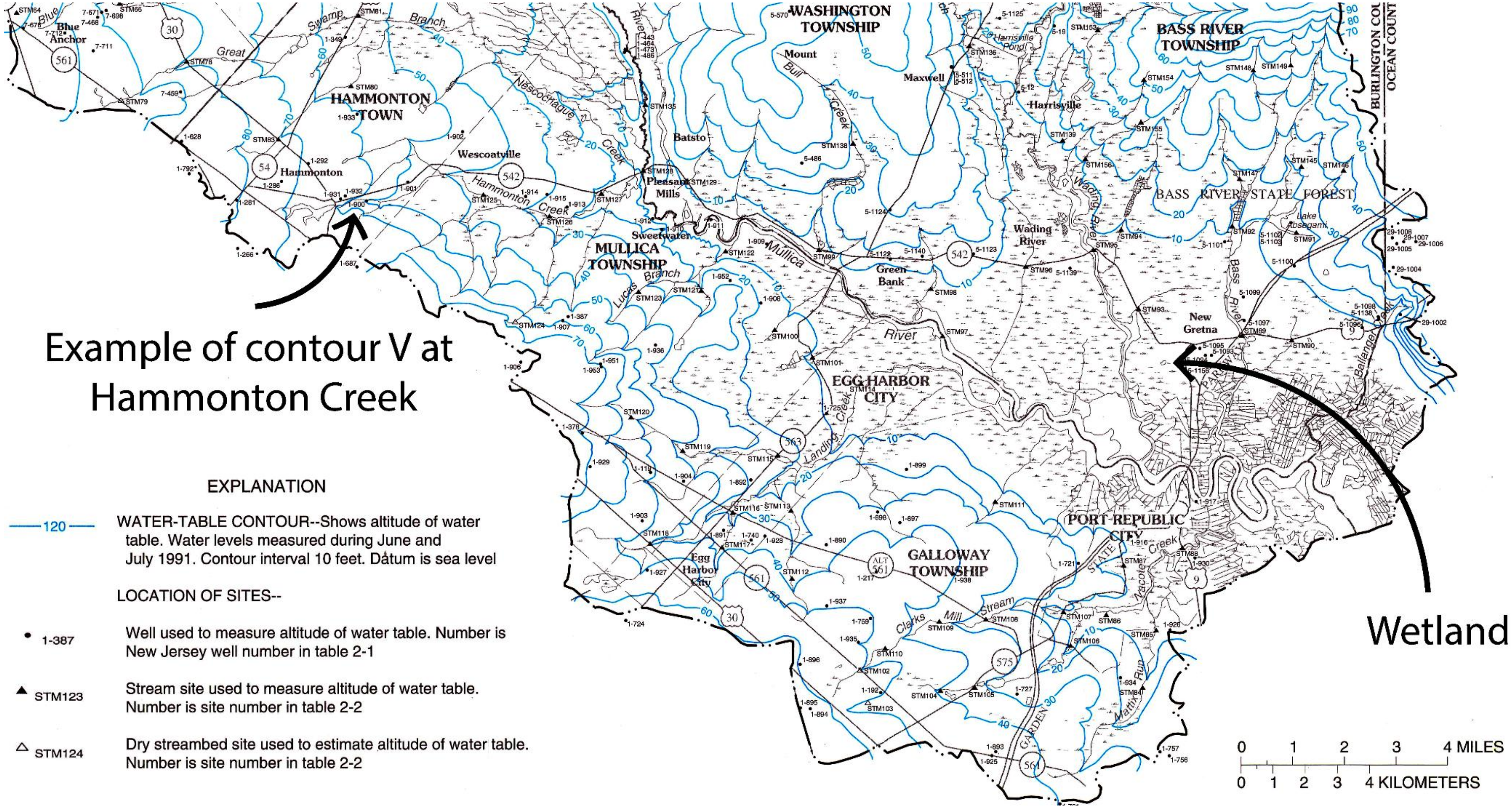


Figure 12 - Groundwater map of the Mullica River Basin in New Jersey, USA, showing multiple rivers and wetlands that are discharge points (Adapted from Johnson & Watt, 1996). Contours in feet, 70 ft ≈ 21.3 m and 10 ft ≈ 3 m.

When closed head contours surround a lake discharge zone, the contours are lower in the interior portion of the zone than on the perimeter. In Figure 10 and Exercise 8, the contour lines around lakes are influenced by the shape of the lake. Even karst caverns need an outlet, such as the spring shown in Figure 13, which likely feeds the Unnamed Tributary. Without this spring, the convergent contours do not have an outlet.

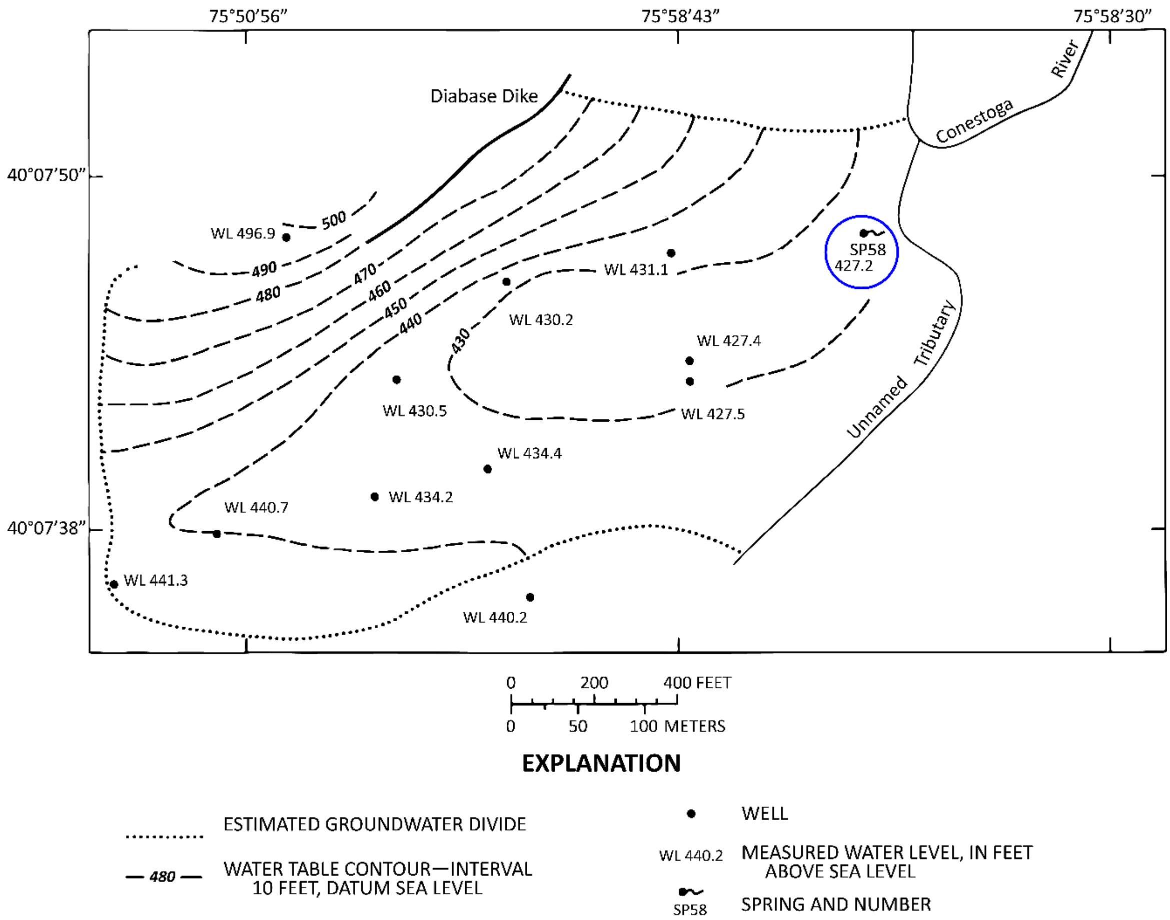


Figure 13 - Groundwater head map in a karst area in the Conestoga River headwaters, Lancaster, Pennsylvania, USA. Contours are head in feet above mean sea level, as measured in wells (dots labeled WL with an associated number) and the spring elevation (SP symbol, circled). Flow based on the contours seem to converge without a surface water outlet, indicating flow through a karst conduit to the spring. There is a hint of a recharge area north of the 500 ft contour to the north-northwest (adapted from Lietman, 1997). 500 ft ≈ 152 m and 430 ft ≈ 131.1 m.

3.1.3 Horizontal Flow Zone Patterns

Horizontal flow zones occur between recharge and discharge areas and their area can be quite extensive. The solution to Exercise 3 revealed that the water levels of wells drilled to different depths in the horizontal flow zone have the same head. In Exercise 7, the map on the left had a horizontal flow zone in a deep aquifer that did not have a connection to a surface stream. Exercise 10⤵, provides an opportunity to identify recharge and discharge areas, and the flow lines connecting them through a horizontal flow zone. Contours in horizontal flow zones are roughly parallel to each other (Figure 6)) but are not necessarily perfectly straight. If there is no change in permeability or thickness of an aquifer, the contour lines in a horizontal flow zone are evenly spaced. Contour spacing decreases where permeability or thickness decrease—as shown in Figure 83 of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗ and in Figure 17 of Graphical Construction of Groundwater Flow Nets↗. Contour spacing increases when permeability or thickness increases. Thus, a change in the contour spacing can suggest a change in the subsurface character of an aquifer. These factors are discussed more in the books cited above.

3.2 Cones of Depression Patterns

A cone of depression that occurs around a pumping well is another pattern that is common on groundwater head contour maps. A cone of depression has concentric contours that decrease toward the center in contrast to the recharge zone that has higher value contour lines in the center (Figure 14). The name comes from the cone shape that the water levels exhibit in cross section.

To draw attention to the direction of decrease on a map, hash marks are sometimes used to indicate a cone of depression, as in Figure 15 of this book and in Figure 65↗ and Figure 87↗ of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow (PDF)↗(Online)↗. In this case the contours are convergent without a surface water feature because the water is removed from the groundwater system and brought to the surface by a pump.

A well should always be indicated on a map in the center of the cone of depression. In the case of multiple pumping wells, the lowest point of the depression occurs somewhere within the well field with its location determined by the combined pumping schedule of all the wells. Automated contouring programs will not necessarily correctly map a cone of depression because there may not be a sufficient number of wells to capture the shape of the cone as well as the regional gradient; thus, careful evaluation is needed when contouring maps that include pumping wells.

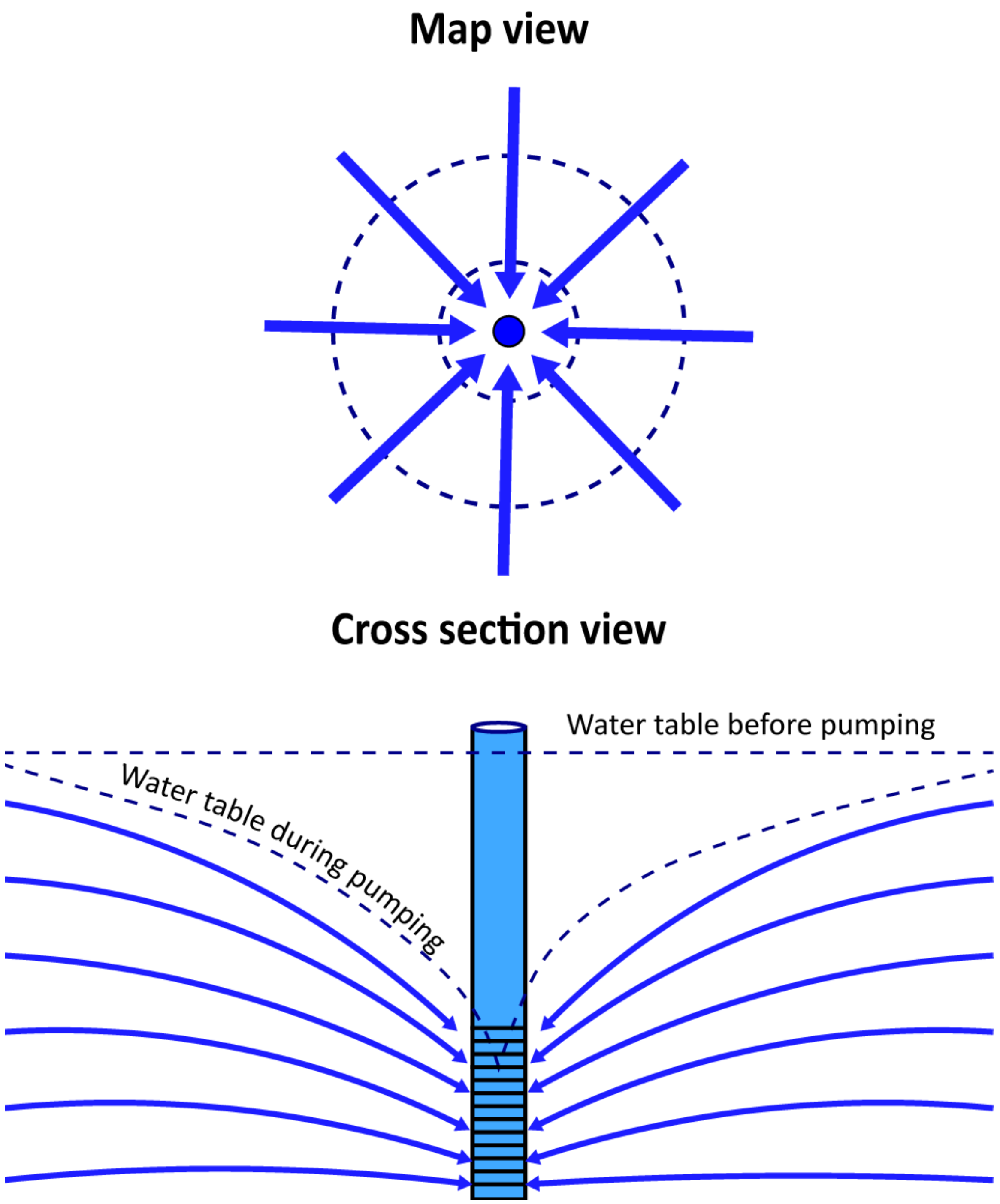


Figure 14 - Cone of depression around a pumping well in map view and cross section in a water-table aquifer. This is similar in a confined aquifer as shown in Figure 84 of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗. The flow lines (arrows) converge on the well in plan view, while in cross section they curve down to the well screen near the well, but are horizontal at a distance from the well.

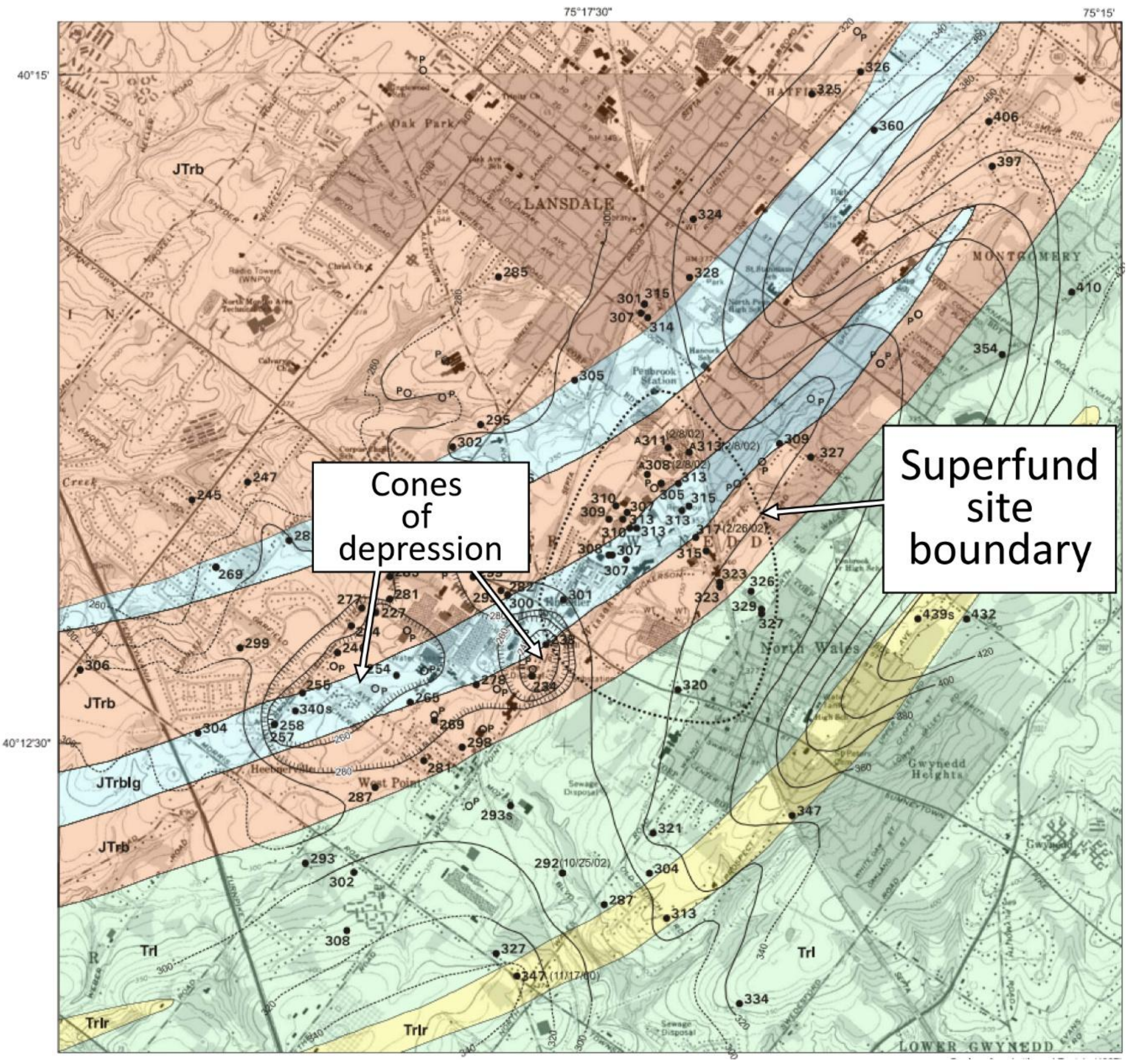


Figure 15 - Cones of depression for pumping wells to remediate a contaminated aquifer in Northern Pennsylvania, USA, are indicated by hatched contours. There are two cones, surrounded by one big cone. Unlike Figure 14, these cones are not circular but oblong, due to fractures creating preferential flow. Color bands are geologic units and contours are groundwater head in feet above mean sea level—350 ft ≈ 106.7 m, 300 ft ≈ 91.4 m (modified and annotated from Senior & Ruddy, 2004).

Mapping groundwater head in aquifers that are pumped is important for considering sustainable development and using pumping to capture groundwater contamination plumes. When water is pumped from an aquifer for water supply (e.g., drinking water; agricultural irrigation; industrial processing), it is expected that the supply will be replenished by recharge to the groundwater system. However, this balance between recharge and pumping needs to be carefully evaluated or the aquifer will be depleted and no longer be a reliable source. The topic of groundwater resource development and sustainability is discussed in Groundwater Resource Development: Effects and Sustainability (PDF)↗(Online)↗.

Mapping cones of depression used to capture plumes is a topic that requires mathematical background beyond what is discussed in this book. A Groundwater Project book on well hydraulics that discusses cones of depression is An Introduction to Hydraulic Testing in Hydrogeology: Basic Pumping, Slug, and Packer Methods (PDF)↗. Capture of groundwater by cones of depression is discussed in Section 12.5.1 of Basic Hydrology: An Introduction to the Fundamentals of Groundwater Science (PDF)↗. Additional techniques for estimating plume capture often involve numerical models (as reviewed in Bair & Lahm, 1996) and the need to account for uncertainty in subsurface properties (Enzenhoefer et al., 2014; Frind & Molson, 2018).

3.3 Geologic Boundary Patterns

Geologic boundaries provide one more piece of information to guide development of groundwater head maps. Sharp contrasts in permeability (more than an order of magnitude) can be barriers to groundwater flow. When a low permeability geologic unit occurs next to a permeable unit, such as bedrock next to unconsolidated sediment or igneous rock next to sedimentary rock, most of the flow will be parallel to the boundary between the two units as indicated by contour lines perpendicular to the boundary. This is illustrated by Figure 16 and in Figure 4 of Graphical Construction of Groundwater Flow Nets↗. Contours perpendicular to bedrock boundaries indicate no flow across the boundary (Figure 16a and northern portion of Figure 16b, whereas a bend in the contours close to the boundary indicates some leakage is occurring (southern portion of Figure 16b). The maps in Figure 16 are both examples of unconsolidated sediment bounded by low permeability bedrock in alluvial valleys, forming a long, somewhat narrow aquifer.

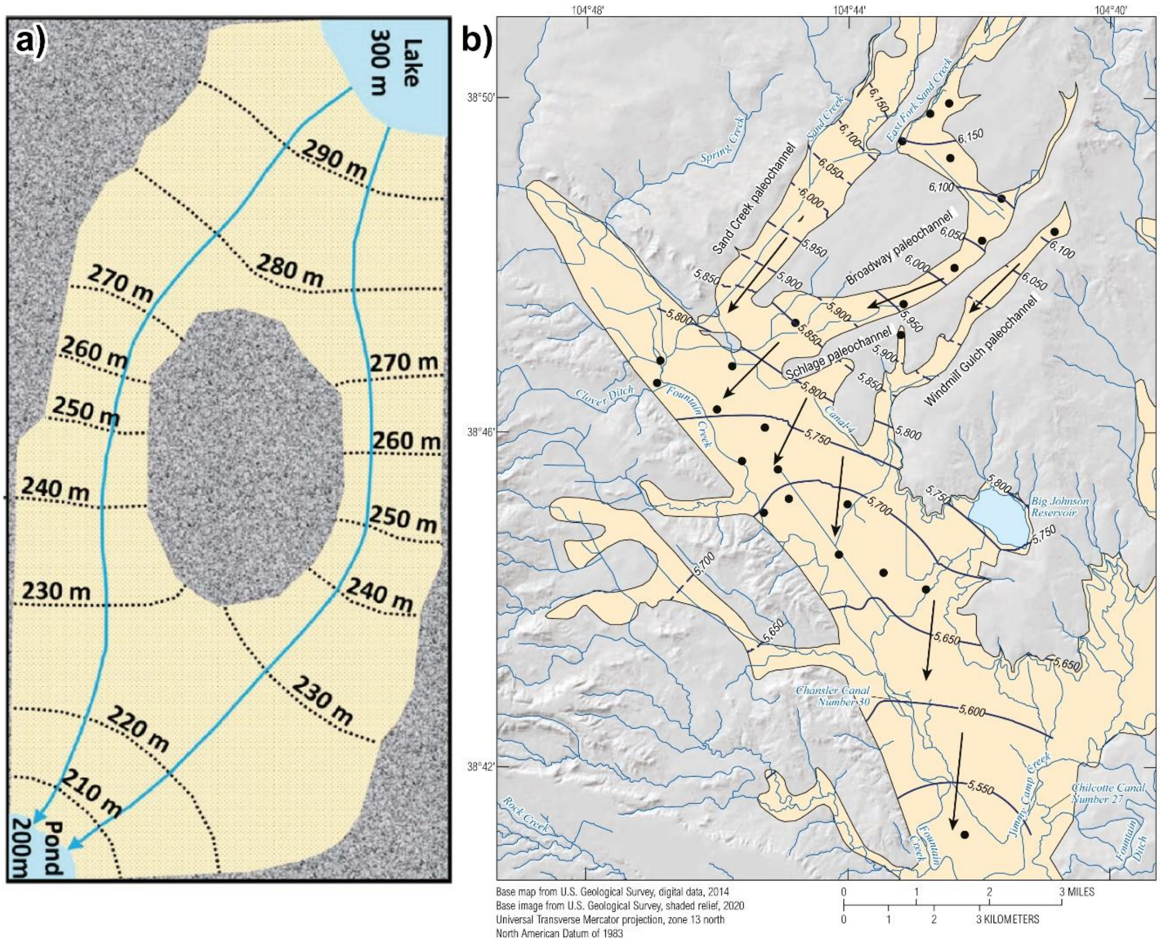


Figure 16 - Influence of a bedrock boundary along an alluvial aquifer. a) A constructed groundwater flow net (from Poeter & Hsieh, 2020↗). b) A contour map of measured groundwater head (from Newman and others, 2024), in feet with 6150 ft ≈ 1875 m and 5550 ft ≈ 1692 m. In this example the authors inferred no leakage between the bedrock and the alluvium along the elongated lobes in the north where contours are drawn perpendicular to the boundary, but inferred leakage across the bedrock boundary in the broad alluvial valley as indicated by the curved contours that are not perpendicular to the bedrock-aquifer boundary.

3.4 Overview of contouring groundwater head maps

There are several principles that can help you draw head contour maps and flow lines as well as identify errors before you finalize a map. More detailed principles for constructing flow nets are provided in Section 2.2 of Graphical Construction of Groundwater Flow Nets↗. Flow systems with variable density groundwater need to be mapped differently because in zones of different density the same value of head will be reflected by different water level elevations, as described in Section 3 of Variable Density Groundwater Flow↗.

Use of a short check list for construction and error checking of head maps facilitates map making by incorporating information in addition to data from wells.

- Flow is always from high head to low head.
- Contours and flow lines tell a story about the groundwater flow system (i.e., where groundwater is coming from and where it is flowing to).

  - Look for recharge and discharge areas and draw head contours to reflect divergent and convergent flow, respectively.
  - Identify information such as surface water features or geologic boundaries that can guide the location of head contours where data are not available.
  - Flow lines should not begin or end in the middle of the map.
  - Look for low permeability geologic boundaries and draw flow lines parallel to these boundaries.
- In isotropic media, flow lines are perpendicular to contours.
- Head contour lines cannot intersect.
- Flow lines cannot intersect.
- A flow line can only cross a head contour line once.
- Contours and flow lines cannot bifurcate.
- Avoid gaps in the map that imply there is no water flow (stagnation zones) unless there is evidence for very slow flow such as in a deep regional flow system.
- Do not contour where you do not have data. When extending lines into such areas, use dashed lines.

Exercise 11↴ provides an opportunity to draw a contour map in the vicinity of a cone of depression. Exercise 12↴ provides examples you can use to test your understanding of head maps.

4 Mapping Plumes and Limitations to Plume Delineation with Head Maps

When a contaminant reaches groundwater and moves with the groundwater, the zone of contamination is referred to as a plume. The word "plume" originated to describe air pollution which often formed a shape like a plume of feathers and the term was transferred to describe contamination underground. Plumes occur when a contaminant source at or near the surface recharges groundwater or when a subsurface source such as a leaking pipe or buried waste dissolves into the groundwater. Landfills are typically constructed at the surface or in the shallow subsurface and usually are designed to stay dry. However, when unintended water enters a landfill, it dissolves contaminants that can leak into the groundwater system. Sometimes the groundwater level rises to saturate a landfill or other waste area that was originally dry.

Typically, the first step in mapping a contaminant plume is producing a groundwater head map. This map is important because it indicates the direction of plume movement, which is not the same as a plume map, but nonetheless key to assessing the plume. Simply stated, the flow lines on a groundwater head map indicate the direction of plume migration (Figure 17). The gradient as determined by the head contour spacing is one factor in determining the rate of plume movement, along with porosity, permeability, and chemical interactions of the contaminant in the system. Groundwater Velocity (PDF)↗(Online)↗ discusses the importance of Darcy's Law and groundwater velocity for mapping plumes, along with methods for measuring groundwater velocity.

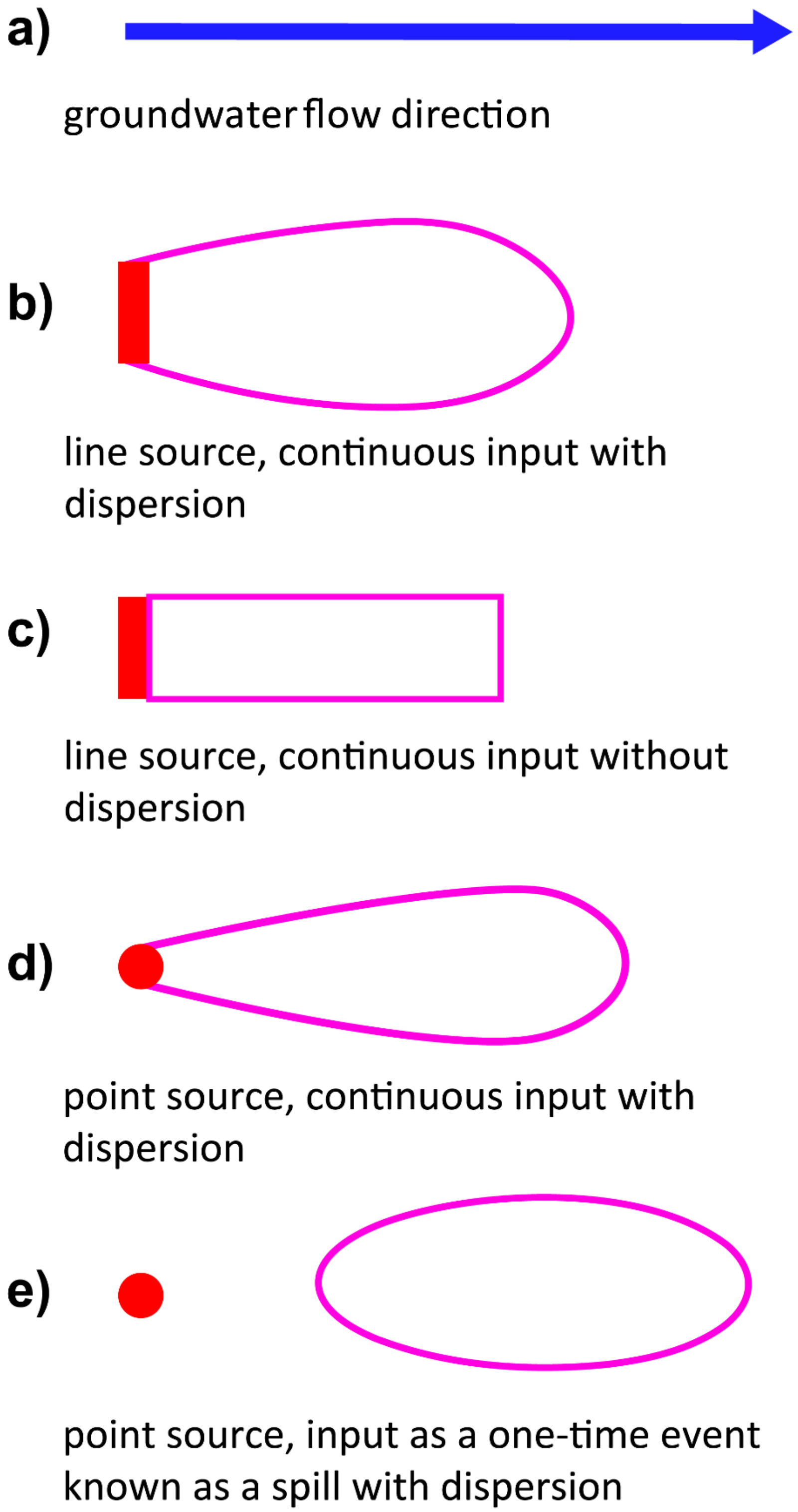


Figure 17 - Plumes drawn along a) a groundwater flow line from: b) a line source with dispersion of the plume; c) a line source without dispersion of the plume which is not realistic; d) a continuous leak from a point source, showing contaminant still coming from the source; and e) a spill at a point, showing the contamination separates from the source location.

That said, there are multiple processes that impact plume shape and concentration. One way to understand the importance of the groundwater head map and the other factors that influence plume migration is to examine the contaminant transport equation. The equation shown here is a simplified one-dimensional equation, which describes concentration of a plume, at a distance x from a continuous source, that spreads only in the direction of flow and not to the sides.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}(Cv) + \frac{\partial}{\partial x}\left(D^* \frac{\partial C}{\partial x}\right)$$

The first term in the equation $\frac{\partial C}{\partial t}$ states the unknown: how does concentration (C) change over time at a distance x from the source). The first term on the right-hand side of the equation $\frac{\partial}{\partial x}(Cv)$ describes how the plume moves due to velocity (v). Darcy's Law provides the linkage to head because $v = \frac{-Ki}{n_e}$ where K is the hydraulic conductivity, a measure of permeability for water, n_e is effective porosity (that is, connected pore spaces), and $-i$ is the hydraulic gradient or change in head over distance. Because the groundwater flows from higher head to lower head, the gradient is negative (that is, the higher head at distance x_1, is subtracted from the lower head at distance x_2). The hydraulic gradient is provided by a groundwater head map. Thus, every map of a groundwater plume is dependent on a groundwater head map. Other data must be collected to measure K and n_e, as discussed in Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow (PDF)↗(Online Section 3 for n_e)↗(Online Section 5 for K)↗. The second term on the right-hand side $\frac{\partial}{\partial x}\left(D^* \frac{\partial C}{\partial x}\right)$ describes how plumes spread due to dispersion and diffusion (D^*, which combines both processes). This term is one of the most difficult to measure because it is dependent on porous media factors at multiple scales. However, it is intuitive to draw plumes that spread out as they travel (Figure 17b) rather than forming a rectangular shape (Figure 17c).

Other terms that can be included in the equation are a sink/source term (e.g., to account for a plume being pumped), decay, and chemical reactions. Decay refers to the transformation of a contaminant to another form, removing it from the plume (albeit sometimes creating another plume consisting of the product of the contaminant decay). Decay will shrink the size of a plume but will not change the direction or rate of travel. Chemical reactions can occur in a plume, and these influence the interactions between the plume and porous media or competing chemicals, as well as toxicity.

An important chemical reaction that influences the rate of plume migration and its shape is retardation, which occurs as a result of reversible sorption of the contaminant to the aquifer solids. Sorption temporarily removes a contaminant from the groundwater, and later releases it when more dilute waters flow through the zone where contaminants are sorbed to solids. When a plume is affected by sorption, it migrates more slowly (depending on the degree of sorption), still following the same direction as groundwater flow. Thus, the plume is referred to as retarded (in other words, slowed). Sorption can be beneficial to cleanup operations by allowing more time to track and design remediation, but sorption can hinder cleanup operations by making it difficult to remove contaminants (slowing release from the aquifer).

An additional chemical property that affects plume movement is density, as discussed in Flow and Distribution of Non-Aqueous Phase Liquids (PDF)↗, Variable-Density Groundwater Flow (PDF)↗(Online)↗ and Box 3 of Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗. These contaminants are often organics that may not fully dissolve in water, forming nonaqueous phases. Plumes from a source of contaminant denser than water can have a nonaqueous phase that may not follow the groundwater flow direction because it is impacted by a different head gradient. These nonaqueous phase contaminants can divide and form multiple secondary source locations, all of which slowly dissolve into the groundwater and form plumes of dissolved contaminates that are driven by the groundwater heads in each location. For example, the source of a dense plume may flow along a bedrock surface that is tilted in the opposite direction of the groundwater gradient. Plumes from a contaminant less dense than water can have a nonaqueous phase that floats on the water table. This nonaqueous phase plume will move in the direction that the water table slopes, volatilizing into the atmosphere and dissolving into the groundwater then migrating in the direction indicated by groundwater heads.

These chemical processes can be considered and used in sketching potential plume maps, but our ability to quantify their effects is varied. For some chemicals, there is information on their rate of decay and there are data describing sorption for specific aquifers. For many chemicals, there is not enough information to accurately predict their decay and sorption nor their interaction with other chemicals in the plume zone and aquifer solids. Given these general principles, Exercise 13↴ explores how groundwater head maps can be used for a preliminary assessment of plume shape.

The flow path of a plume is also affected by variations in permeability (referred to as heterogeneity). Plume boundaries can have an irregular shape or split into fingers. Some, but not all, variations in permeability may be expressed in the groundwater head map (as illustrated by Figure 19 of Devlin, 2020↗); more commonly, the groundwater head map does not pick up the scale of variation that influences plume shape. For this reason, more wells are typically needed to map a plume than to map groundwater heads. Understanding heterogeneity is important to predicting plume movement and the variability in permeability values presents challenges to characterization (as discussed in Section 5 of Woessner & Poeter, 2020↗ and in the model construction descriptions of Brandenburg, 2020↗)). Particularly challenging are the extreme contrasts in permeability observed in fractured aquifers (as shown in Figure 28 of Devlin, 2020↗) and karst systems (Kuniansky et al., 2022, Section 3 Online↗). The high permeability of a fracture or karst conduit creates "superhighways" for plume movement in groundwater. Plumes follow the direction of groundwater head maps, if any anisotropy of hydraulic conductivity is accounted for, however these “superhighways” are often difficult to identify in head maps because monitoring wells are commonly too far apart to reveal contour shapes caused by “superhighways”.

Groundwater head differences between aquifers is important for evaluating threats to neighboring aquifers. A contaminated aquifer above a deeper aquifer will threaten the deeper aquifer when 1) the head is higher in the shallow aquifer or 2) the contaminant is denser than water and can sink. An aquitard (low permeability unit) between two aquifers provides a layer of protection to slow or prevent contamination from spreading. However, aquitards can be breached by fractures and by drilling wells that are not sealed properly. These issues are considered in Exercise 9 which examines the head difference between the shallow and deep aquifer at the north end of Love Canal, indicating the direction of flow is downward. The rate of flow was determined to be slow due to the low permeability and thickness of the aquitard (Mercer et al., 1983).

For more quantitative assessment of plumes, a variety of analytical and numerical solutions are available (Javandel et al., 1984; Konikow, 2011; Srinivasan et al., 2007). An initial assessment using a groundwater head map can help determine useful locations for additional monitoring wells. Understanding the relationship between groundwater head maps and plumes can provide a check on the logic of plume maps made with limited contaminant monitoring points. For example, the size of the source area affects plume boundaries, with plumes from point sources (i.e., sources of small extent) typically exhibiting an appearance of more spreading (Figure 17d) than a line source (Figure 17b) that has a wide central area of high concentration due to the geometry of the source area. Also, a plume that results from a continuous leak will be connected to the source area, but a spill (that is, introduction of contaminant as an isolated event over a short period) has a limited volume of contaminant and the plume moves away from the source area once the contaminants are mobilized by groundwater flow (Figure 17e).

5 Wrap-up

When you want to find out about an aquifer, the groundwater head map is a good place to start. The contours and associated flow lines tell a story about where the water is coming from and going to. Drilling logs from wells used to create the map will provide information about aquifer thickness, aquifer depth, and surrounding formations. These maps are used in reports and research papers to provide key background information on aquifers.

To construct groundwater head maps, wells are needed to provide water level data, and a log of the geologic units encountered. The log is important to ensure that the wells used in the map are from the same aquifer. Hydrogeologists can use known boundary conditions such as surface water features and mapped extent of the aquifer to fill in gaps in well data. They also use known patterns for recharge areas, discharge areas, pumping wells, and horizontal flow zones to construct contour maps that make sense hydrogeologically. Exercise 14⤵ provides an opportunity to do a site evaluation and construct a groundwater head map based on these principles.

Even if you are not constructing a map, being able to read the maps that are provided in reports is an important skill to check whether the map is providing a logical interpretation of a groundwater flow system. This book provides Exercises that can develop your ability to spot errors and improve groundwater head maps. It is not uncommon to find errors in interpreting well data because the map was made without proper consideration of the groundwater flow system. For instance, flow lines might not end at a discharge area, or recharge is located where a parking lot or other flow constrictions occur. You can find groundwater head maps in USGS reports, state geological survey reports, consulting reports, university theses, and research papers. The USGS in particular has a long history of producing groundwater head maps in every state, most of which are accessible online to download.

Understanding and interpreting groundwater head maps is important for a variety of tasks a hydrogeologist needs to perform. Groundwater-surface water interaction is important both for understanding how contaminants can spread from one resource to another and also for predicting water supply as streams are threatened by changes in climate (Winter et al., 1998). Groundwater head maps help explain the connections between groundwater and surface water. There are many challenges with tracking plumes in groundwater and protecting groundwater supplies. The risk levels are not well established (McBean, 2023↗). Furthermore, cleanup operations are costly, both in terms of litigation and engineering, yet they may not be effective; prevention of plume spreading and good data are an important tool for the difficult challenge of protecting groundwater (Freeze, 2000). Plume tracking begins with an understanding of the groundwater flow directions, obtained from a groundwater head map.

For both contaminant transport and groundwater resource development, pumping tests are often performed to establish the permeability of an aquifer. A groundwater head map can aid in design of the pumping test (establishing background gradient, locating wells for monitoring). More elaborate tracer tests are sometimes used to obtain data for groundwater models and knowing the background gradient is important in their design.

Understanding and mapping how groundwater heads can change over time is critical to protecting our water resources. One of the first steps in site evaluation is often to find an existing groundwater head map, or create one. This book is designed to make that step more accessible.

6 Exercises

Exercise 1: Measuring head in a well

A spreadsheet titled "UsingGroundwaterHeadMaps-Exercise-1and2.xlsx" that provides these data in a table that you can use for developing your answers to Exercise 1 and 2 is provided for download on the book page↗.

a) What is the head in each well in meters (m)? (Hint: use of consistent units is essential).
b) What is indicated when the casing elevation is negative?

Well ID	Land surface elevation (m)	Casing stick-up or height, units vary	Depth to water (m)	Head (m)
MW1	125	0.3 m	21.6	
MW2	48	-4 inches	12.5	
MW3	327	1.25 ft	62.1	

Click for solution to Exercise 1↴

Return to where text linked to Exercise 1↥

Exercise 2: Finding the open interval in a well

A spreadsheet titled "UsingGroundwaterHeadMaps-Exercise-1and2.xlsx" that provides these data in a table that you can use for developing your answers to Exercise 1 and 2 is provided for download on the book page↗.

a) What is the open interval for each well of Exercise 1? This data is from the USA where drillers typically use feet and have casing in 5 ft lengths, so the casing length is multiples of five.
b) Which wells do you think are screened and which have an open hole?
c) Which wells have their water level in the casing, and which have their water level in the open interval? (Hint: casing depth can be converted to meters for comparison to the depth of water in Exercise 1).

Well ID	Depth of well (ft)	Depth of casing (ft)	Open interval (ft)	Open interval (m)	Depth to water from Exercise 1 (m)
MW1	85	80			
MW2	60	50			
MW3	328	100			

Click for solution to Exercise 2↴

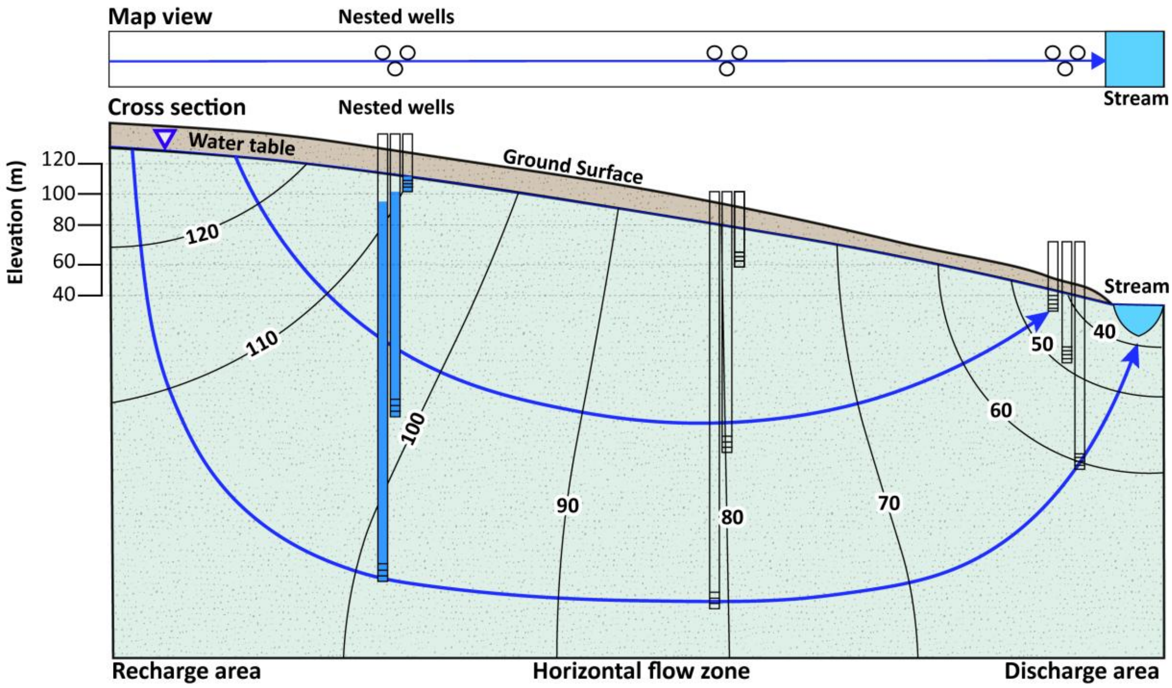
Return to where text linked to Exercise 2↥

Exercise 3: Heads in multi-level wells

Here, Figure 5 is shown with additional information for this exercise. In this version, there are three nests of 3 wells each drilled to a different depth with a short screen at the bottom in the recharge, horizontal flow, and discharge areas.

a) Draw on the cross section to indicate the water level in each of the wells in the horizontal flow zone and in the discharge area.

b) What is the relative head at each depth and in each zone and what does that tell us about the direction of groundwater flow?



Click for solution to Exercise 3

Return to where text linked to Exercise 3

Exercise 4: Variation in head over time (using USGS monitoring wells)

Four years of water level data from two USGS monitoring wells are provided in the MS-Excel spreadsheet (UsingGroundwaterHeadMaps-Exercise-4.xlsx) that can be downloaded from the book page↗.

a) How do the data look when plotted on a graph of head versus time? By using the axis option "Values in reverse order", high depth to water (deep water level) will be on the lower part of the axis and shallow depth to water (shallow water level) will be higher on the plot. Thus, plotting in reverse order mimics water level rise and fall.

In many northern hemisphere countries, the water year starts on October 1 and ends on September 30 to capture the cycle of runoff: precipitation occurring in the fall does not tend to drain until after the winter so fall is considered the start of annual patterns.

b) What is the average monthly water level for each year in Oct and July and how do they differ?
c) What is the average water level for each water year?
d) What are the range of values? You can calculate by finding the difference between maximum and minimum values and by finding the average variation (using absolute value).
e) Is there more seasonal or annual variation?
f) Are the answers to questions (b) through (e) the same for each well?
g) How could this information be used when selecting data for creating a plan-view groundwater head map?

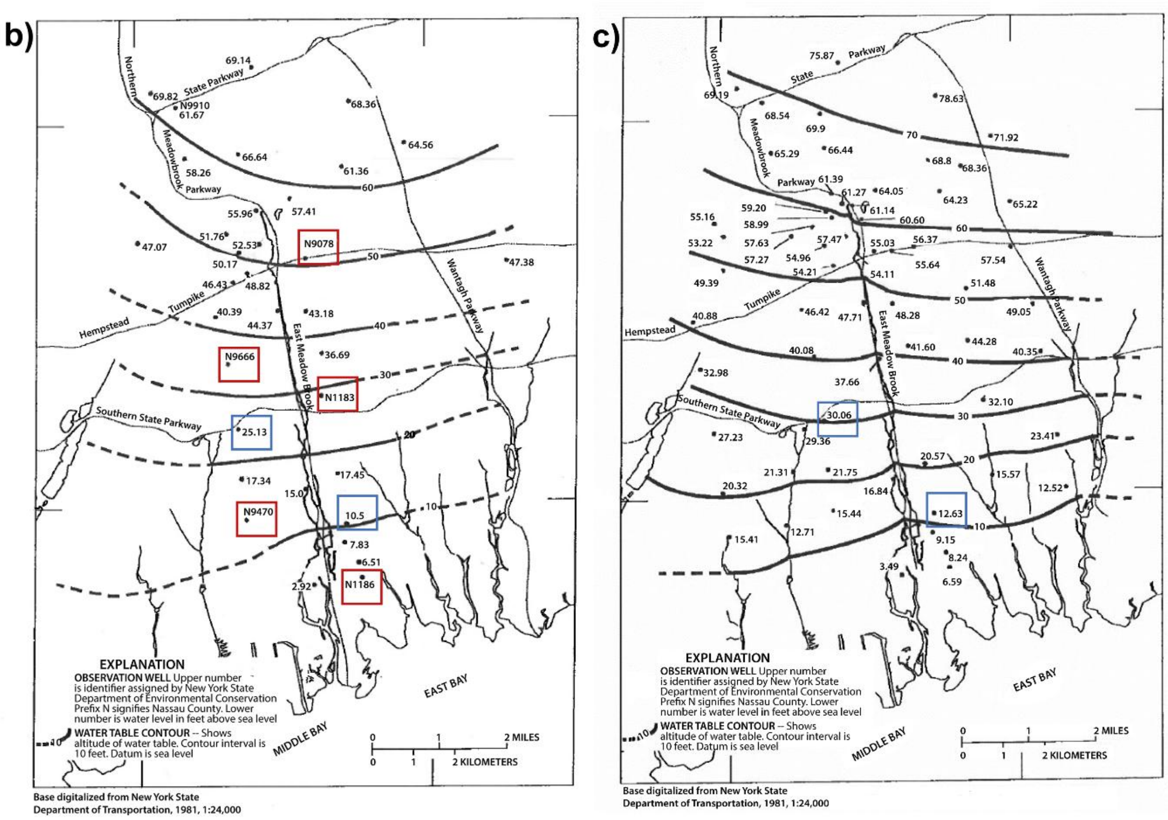
Click for solution to Exercise 4

Return to where text linked to Exercise 4

Exercise 5: Relating head to contour maps

Exploring the head maps shown in Figure 6b and Figure 6c (reproduced here for the reader's convenience) is useful in developing and understanding of head maps.

a) What is the water level of the bay shown in Figure 6?
b) Using the head map shown in Figure 6, estimate the head (water level) values for the listed wells indicated by red boxes N9078, N9686, N1183, N940, N1186.
c) How much did the water levels change from autumn of 1988 to autumn of 1990 for the wells indicated by the red and blue boxes of Figure 6?
d) Did the overall pattern of the contours change?

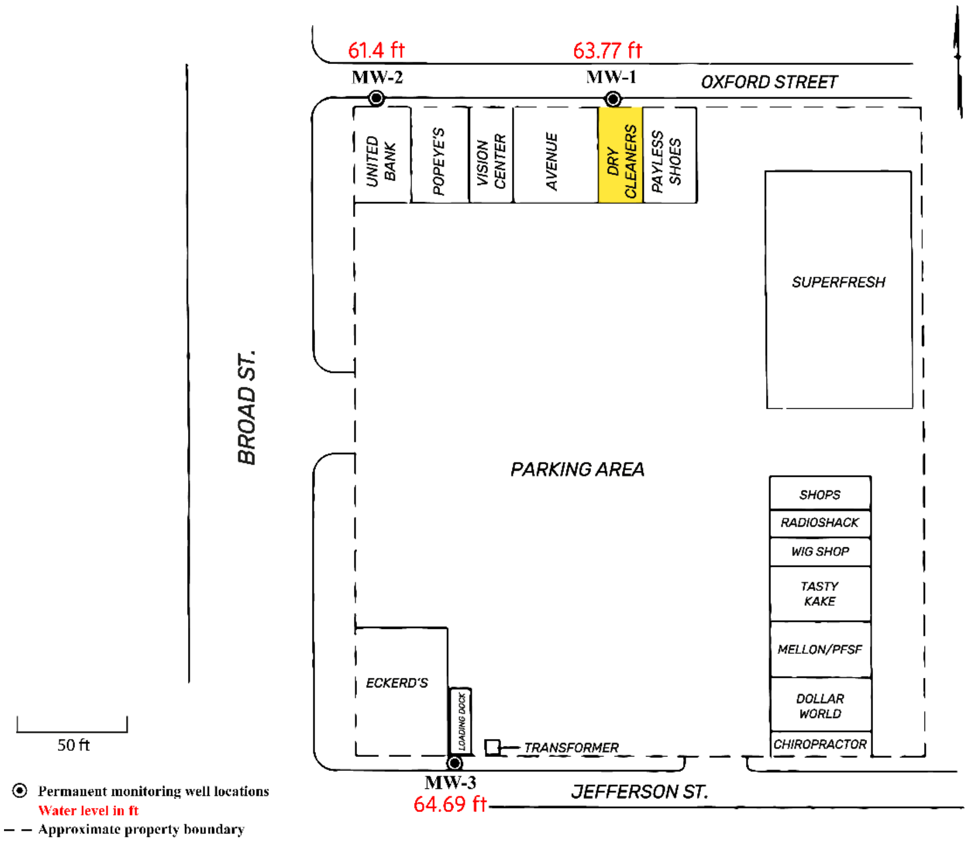


[Click for solution to Exercise 5]
[Return to where text linked to Exercise 5]

Exercise 6: Contouring with only 3 measurements (3-point problem)

Solve the 3-point problem using Figure 7, which is provided below. As a first approximation, you can estimate the spacing between the contours (e.g., by noting that the 64 ft contour will be closer to 63.77 than to 64.69) and putting the appropriate number of contours between each well as described in the text. Alternately, you can calculate the spacing based on the scale bar, the distances between the wells, and the head values at each well. When the map is complete, you can answer the questions to evaluate the direction of groundwater flow and where contamination from the Dry Cleaners might be found.

a) Contour groundwater head beneath the shopping plaza and label each line with your contour interval.
b) Draw arrows perpendicular to contours to indicate the estimated direction of groundwater flow.
c) Which wells likely show contamination?
d) Which wells likely do not show contamination?

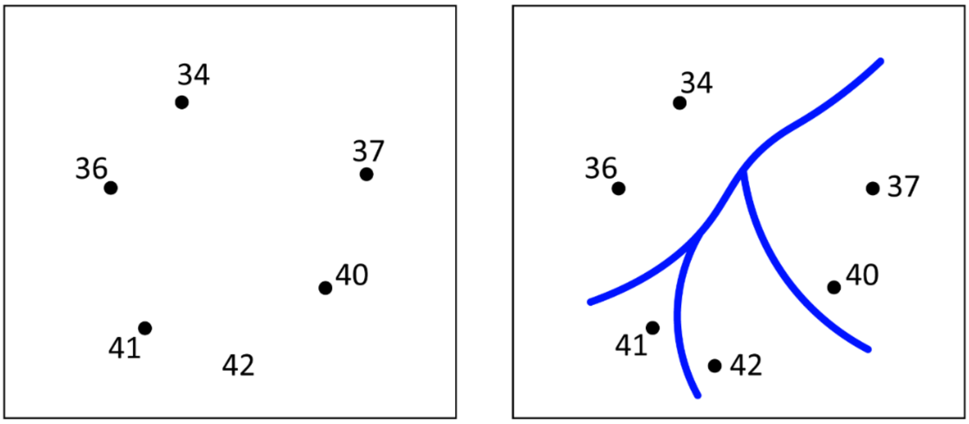


Click for solution to Exercise 6

Return to where text linked to Exercise 6

Exercise 7: Contouring near stream discharge areas

When groundwater discharges to a stream as shown in cross section in Figure 5, contours of head need to reflect that relationship even if there are not enough wells to show that the contours form a V (Figure 8b and Figure 9a). Draw the appropriate contours in each map panel below. First, draw contours for a case where there is no stream or groundwater is deeper than the stream and not discharging to the stream. Then on the map that shows a stream, draw contours for the same set of head data that indicate groundwater discharging to the stream (remember the rule of V's). Although the well data are the same, the knowledge about groundwater-surface water interaction should influence how the contours are drawn.

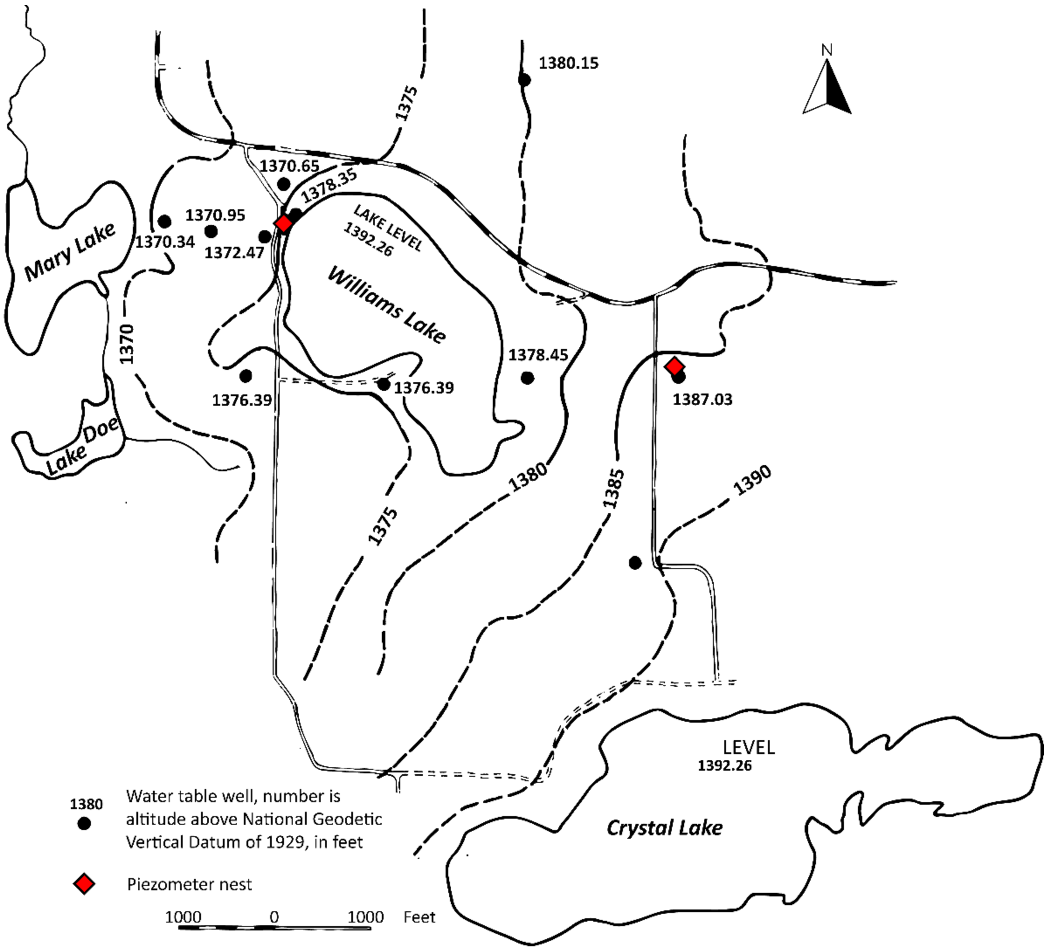


Click for solution to Exercise 7

Return to where text linked to Exercise 7

Exercise 8: Flow lines near a lake

Is Williams Lake receiving groundwater discharge or recharging the aquifer? Draw flow lines on the map to answer the question.



(Modified from Siegel & Winter, 1980).

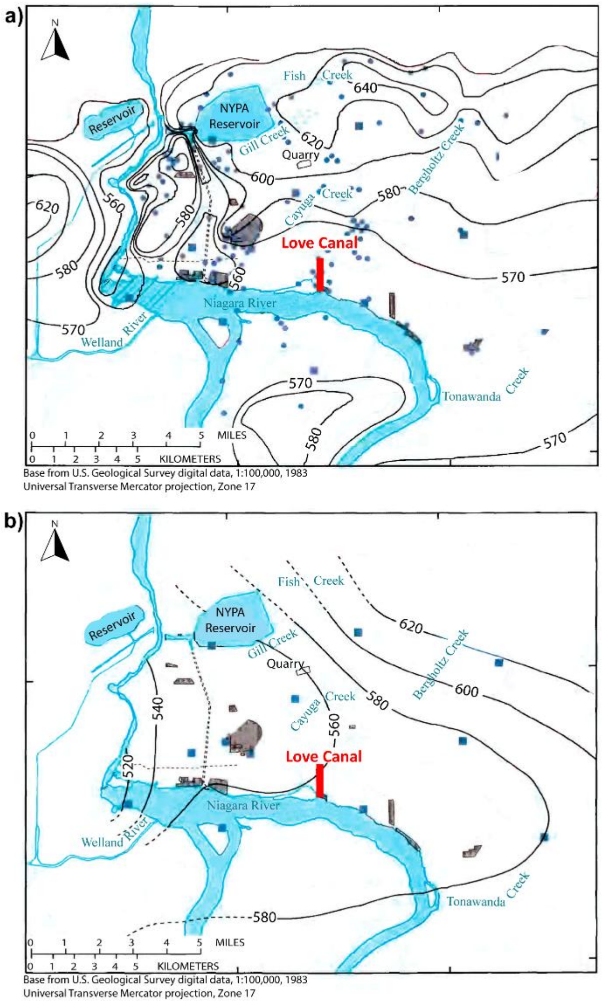
Click for solution to Exercise 8⤵

Return to where text linked to Exercise 8⤴

Exercise 9: Interpreting contours in a multi-layer system

Examine the shallow and deep aquifer head maps near Love Canal (Figure 4, repeated below for the reader's convenience) and determine the following. The maps show groundwater head for a) the shallow (overburden) and b) deep (dolomite) aquifer.

a) What is the highest and lowest head contour mapped in the overburden aquifer?
b) What is the highest and lowest head contour mapped in the lower dolomite aquifer?
c) Is there potential for flow from the upper to lower aquifer?
d) What is the estimated head at the north end of Love Canal in each aquifer?
e) Draw three or four flow lines from areas of high water level to areas of low water levels on each map.
f) Where are the high heads in the lower dolomite aquifer and what is the direction of flow from that area?
g) Where are the high heads in the overburden and what is the direction of flow from that area? How does it compare to the lower dolomite aquifer?

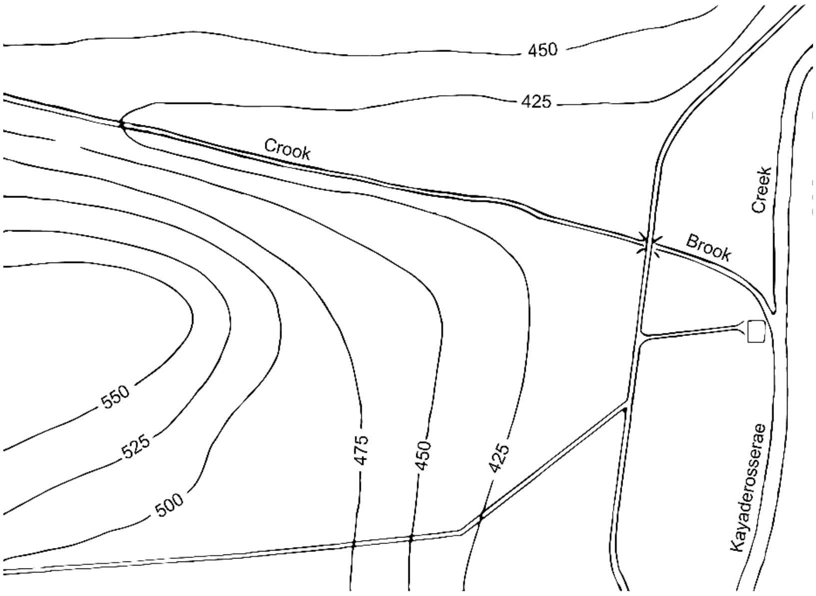


Click for solution to Exercise 9↓

Return to where text linked to Exercise 9↑

Exercise 10: Identifying recharge and discharge areas from contours

Identify the recharge and discharge areas on the map below by drawing some flow lines and indicating the recharge area with shading and the letter R and the discharge area with the letter D.

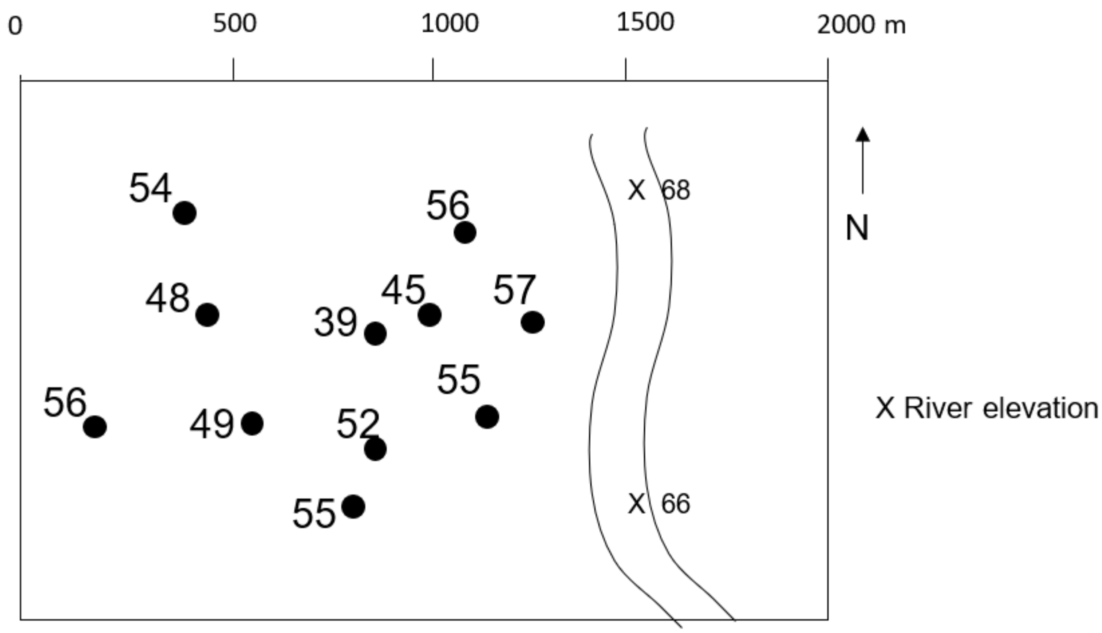


(Modified from Mack et al., 1964).

[Click for solution to Exercise 10](#)
[Return to where text linked to Exercise 10](#)

Exercise 11: Contouring a cone of depression near a boundary

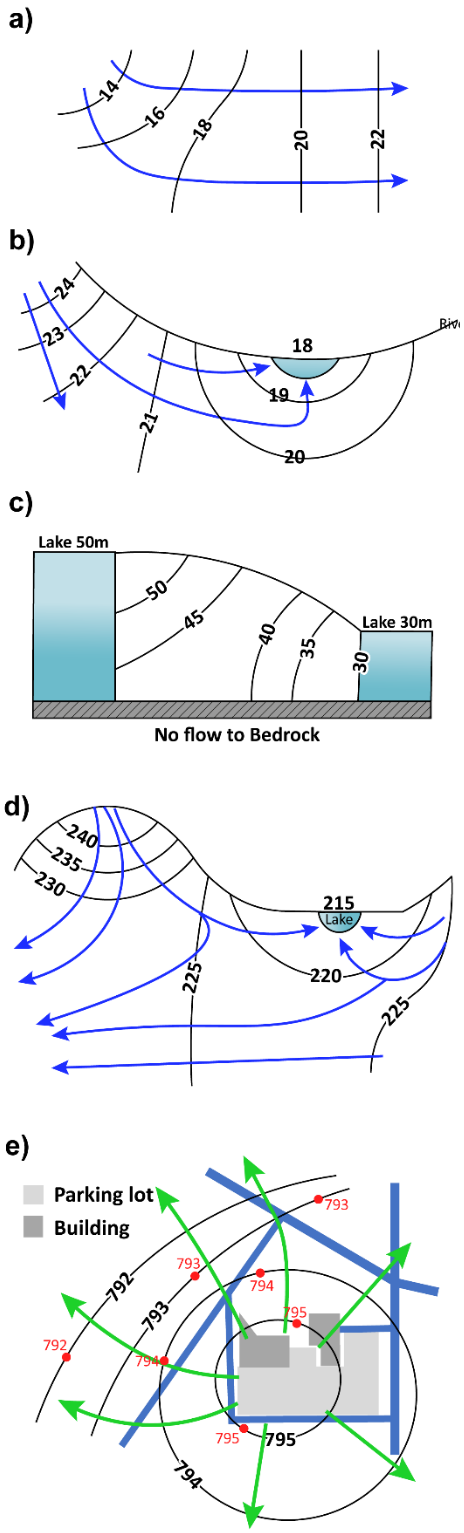
a) Contour the well data near a pumping well and a perennial stream shown in the image below.
b) Where is the pumping well?
c) How does the stream affect the cone of the depression?
d) Does the cone of depression differ between well and the stream as compared to the area on the other side of the well? If so, where is it steeper and why?



Click for solution to Exercise 11
Return to where text linked to Exercise 11

Exercise 12: Identifying errors in head contouring

Review the following head contour maps and list the errors. The errors may occur in the head contours or the flow lines.



Click for solution to Exercise 12

Return to where text linked to Exercise 12

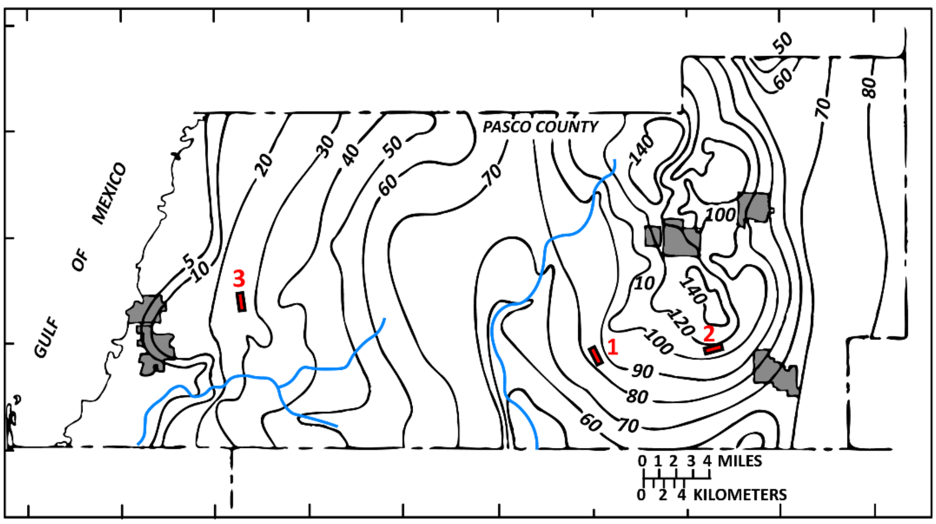
Exercise 13: Estimating plume shapes from groundwater contours

This map is provided so you can sketch conceptualizations of plumes given the information about each contaminant source. Take whatever liberty you want regarding: when the source was introduced, its strength (i.e., the mass and volume of contaminants introduced), the groundwater velocity, the amount of time that has passed since the source was introduced. If you would like, you can provide comments on why you drew the plumes the way you did. The goal is to match the plume directions to groundwater head maps and to match the source area descriptions to the expected plume shape.

a) Start by drawing flow arrows from each source area. Then draw the plumes for the cases listed.

b) Draw plumes reflecting the flow direction as well as the nature of the source and the dispersivity of the system.
SOURCE AREA 1: two plumes emanate from this location, 1) a continuous source and 2) a spill (source that is no longer leaking).
SOURCE AREA 2: one continuous source occurs at this location, but sketch two plumes, 1) assuming that dispersion is small and 2) assuming dispersion is large
SOURCE AREA 3: three, line source spills are introduced at the same time at this location 1) contaminant is not retarded, 2) contaminant is retarded due to sorption on aquifer solids, and 3) contaminant decays with a half-life that is somewhat less than the duration of the source.

What features on this map would be threatened by the plumes you drew given that blue indicates surface water features and gray indicates developed areas?



EXPLANATION

—— 20 —— LINE OF EQUAL WATER TABLE ELEVATION ABOVE SEA LEVEL IN SEPTEMBER 1984
CONTOUR INTERVAL 5 AND 10 FEET

Map modified and annotated from Fretwell, 1988.

Click for solution to Exercise 13

Return to where text linked to Exercise 13

Exercise 14: Evaluating hazardous waste site cross section and groundwater head maps

Background

A plant that recycles solvents operated for nine years near Seymour, Indiana. When the company went bankrupt in 1980, the owners abandoned about 100 tanks and 50,000 drums filled with solvents. The drums and tanks leaked an unknown amount of liquid organic compounds into the soil. Recharging precipitation moved the contaminants through the soil zone to the groundwater.

The EPA designated the area as a Superfund site in 1983 to help guide monitoring and clean up (USEPA (n.d.)↗). There were both public and private wells in the area in addition to surface water that were threatened by the plume. About 100 homeowners who had wells nearby were put on a public water supply. Since closure of the site, waste and topsoil have been removed, a cap emplaced, and pumping wells installed to help control migration of the plume. Reviews have been conducted every five years to evaluate the status of the plume and human health protection measures.

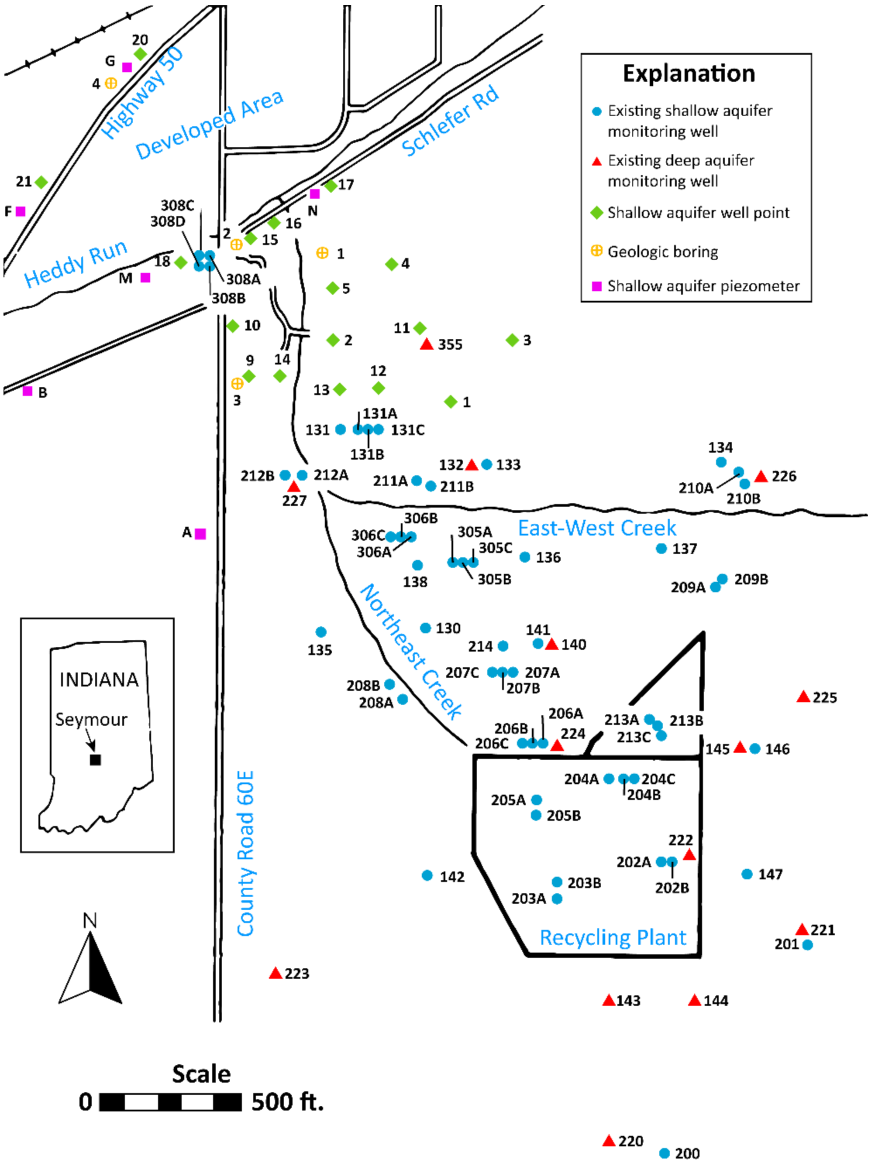
An understanding of groundwater flow paths was needed to design the remediation system and evaluate potential threats to the water supply. This Exercise provides field data from the Superfund site and activities used to investigate groundwater flow paths. The first steps of the exercise provide familiarity with the underlying geology and maps of wells used to characterize the site. Then you are asked to make a geologic cross section to identify local aquifers and aquitards. Next, you are asked to make groundwater head maps to identify the directions that plumes may migrate. Associated activities include estimating the head gradient and average groundwater velocity.

a) Geologic Setting and Well Map

The site is located on about 70 to 80 ft (≈ 21 to 24 m) of unconsolidated glacial-fluvial deposits. These deposits overly shale bedrock of very low hydraulic conductivity and forms a lower "no flow" boundary for the unconsolidated aquifer. Glacial deposits can form both aquifers and aquitards due to variations in grain size, sorting, and thickness. Well logs (descriptions of sediment from drilled wells) are used to interpret subsurface units.

Nearly 100 wells were drilled to characterize the site. The wells served different purposes as indicated by the map legend. Some were drilled for geologic information and to find depth to bedrock. Some were drilled to measure water levels in a shallow aquifer on the site and some were drilled to measure water levels in a deep aquifer. Others were drilled to sample the plume. Wells were added over time with some new wells inserted between older wells, which leads to a numbering scheme that can be difficult to follow.

At least three copies of the site map provided with this exercise are needed to complete the tasks in this exercise. To find the wells with data for a specific part of the exercise, it is useful to familiarize yourself with the map and circle the wells for each dataset. Field sites often have extraneous information that needs to be sorted through in order to complete the necessary tasks. **<u>Create three maps. On the first map, circle the wells on one map where borehole data are available (GB2, GB2, 227, 224, 222, 221). On the second map, circle wells that reflect water levels for the shallow zone. On the third map, circle wells that reflect water levels for the deep zone.</u>**



b) Hydrogeologic Interpretation Based on Making a Cross Section

After becoming familiar with the map in part (a), the next step is to construct a geologic cross section of the site to identify the key hydrostratigraphic units that must be considered for plume movement. A hydrostratigraphic unit is either an aquifer or an aquitard. Laterally continuous aquitards form a confining bed. For this exercise, assume all of the units are groundwater-bearing and are either aquifers or aquitards (confining beds).

Field workers on the drilling team make a quick identification of the material from depth intervals in the well and cannot always distinguish between hydrostratigraphic units. However, by paying attention to changing descriptions with depth, one can usually identify layering of higher and lower permeability units that form aquifers and aquitards.

The table of geologic boring (GB) logs included for this exercise provides data on grain size and sorting for depth intervals of a number of wells. The two letter indicators are based on the Unified Soil Classification System, which is described in the next table.

Geologic boring (GB) logs, depths in ft

Well ID and depths	Descriptions, GE = ground elevation
GB-2	**GE 562**
0–7	clay and silty sand (SM-SC)[1]
7–68	fine to medium sand (SP)
68-70	shale bedrock
GB-3	**GE 565**
0–7	fine silty sand (SM)
7–60	fine to coarse sand (SP)
60–61	clay and silt (ML-CL)
227	**GE 562.6**
0–6.5	artificial fill
6.5–9	medium to coarse silty sand (SM)
9–16.5	medium sand to medium gravel (SP-GP)
16.5–25.5	coarse to medium sand (SP)
25.5–27	sandy clay (SC)
27–36	medium to fine sand (SP)
36–66	clay to clayey silt, low plasticity (CL-ML)
66–67.5	medium gravel to find sand (GP-SP)
67.5	bedrock
224	**GE 564.5**
0–5	fine to medium sand, silty (SM)
5–15.7	coarse to fine sand, some sandy silt (SP-SM)
15.7–18	silt with low plasticity (ML)
18–39.5	fine to medium sand, some sandy silt (SP-SM)
39.5–65.5	interbedded silt (ML) and clay (CL) with low plasticity
65.5–69.5	medium to coarse sand (SP)
69.5	shale bedrock
222	**GE 568**
0–3	artificial fill
3–19.5	fine to medium sand, some sandy to silty clay (SP-SC)
19.5–22	silt, low plasticity (ML)
22–26	fine sand, some sandy silt (SP-SM)
26–51.5	silt and clay, low plasticity (ML-CL)
51.5–63.5	medium sand (SW)
63.5–73.5	medium gravel to sand (GP)
73.5	red shale bedrock
221	**GE 569.8**
0–10.5	sandy, silty clay (SC)
10.5–33	coarse to fine sand (SP)
33–55.5	interbedded clayey silt and sandy clay with low plasticity (ML-CL)
55.5–63.5	coarse to fine sand (SP)
63.5-74	gravel, mixed with sand (GP)
74-76	red shale bedrock

The Unified Soil Classification System uses two letters. This table explains how to use the system to identify aquifers and aquitards. Sometimes the first letter dominates the

[1] The next table explains the Unified Soil Classification System abbreviations used in this table

description, and sometimes the second letter dominates. The second letter determines which letter is dominant. Many of the boring logs list two soil types for each interval. If these soil types conflict in terms of whether they would typically be an aquifer or aquitard, consider whether one sounds dominant in the description, and if neither sounds dominant, then associate the material with the nearest neighbor (that is, if low permeability material is nearby, assume it continues in the zone under consideration).

How to use the Unified Soil Classification System to identify Aquifers and Aquitards

First letter	Second letter	Aquifer/Aquitard	Reasoning
G for gravel	P or W for poorly sorted or well sorted	Aquifer	Gravel has high permeability. It will appear as the first letter, then the sorting is described. Both well sorted and poorly sorted gravel are aquifers.
S for sand	P or W for poorly sorted or well sorted	Aquifer	When S is followed by P or W, then sand is the dominant sediment. It has high permeability. Both well sorted and poorly sorted sands are aquifers.
S for sandy	M or C for silt or clay	SC is an Aquitard. SM is typically an Aquitard but not always.	When S is followed by M or C, then S is an adjective (i.e., sandy) rather than a noun (i.e., sand), and the dominant sediment is silt or clay. Sandy clay is always an aquitard. Sandy silt is often an aquitard, especially when associated with nearby clay. However, sandy silt can be an aquifer.
M for silt	H or L for high or low plasticity	MH and ML are typically aquitards.	Silt is dominant and these are typically aquitards, especially when there is clay nearby. Occasionally silt may be considered an aquifer. Low plasticity may have more silt, and high plasticity may have more clay.
C for clay	H or L for high or low plasticity	CH and CL are aquitards.	Clay is always an aquitard. Low plasticity may have more silt, and high plasticity may have more clay.
Artificial fill	Not classified		Unknown. Fill can be high or low permeability. Fill often occurs in lenses.

Questions about the Unified Soil Classification System

1) Is a unit labeled MC an aquitard or aquifer?
2) Is a unit that has S as the first letter an aquifer or aquitard?
3) Is a unit labeled GP an aquifer or aquitard?

Create the cross section

- Use the maps developed in (a) to identify a roughly NW–SE cross section. Estimate the distances between the mapped wells.
- Sketch the well locations on a scaled cross section (it may help to use graph paper). Use the deepest well to set the length of the vertical axis of the cross section. It is useful to draw a cross section using a vertical exaggeration such that a unit on the vertical axis is spread over a larger portion of paper relative to the same unit on the horizontal axis. In this case a 10:1 vertical exaggeration will result in a workable cross section, but the vertical exaggeration can be different on your version.
- Draw a vertical pair of lines for each well at the appropriate location and label the well at the top (the width of the well does not need to be to scale, but the distances between the wells and depth of wells should be to scale). Next use the USCS sediment

descriptions listed in the table for each well to characterize the material as either fine or coarse and indicate that at the correct depths on the sketched cross section. Label the depth of bedrock at the bottom of the well if it is provided in the data.

- Draw lines between the wells connecting units that have similar grain size and label each as an aquifer or aquitard. Draw a line along the bedrock boundary. This process is referred to as correlating geologic units. The goal is to find similarities between units that suggest similar permeability, not distinctions. By lumping similar units, a layered cross section of aquifers and aquitards is defined. Occasionally there may be a small lens of dissimilar material, but unless the same unit occurs in multiple wells, it is best not to designate it as a separate layer.

Questions about the Completed Cross Section

4) Is there one or more aquitards? Describe the unit(s) in terms lithology (grains size or rock type) and bedding. Bedding refers to the geometry and thickness of the layers.

5) Is there one or more aquifers? Describe the unit(s) in terms of lithology and bedding.

6) How might the presence of an aquitard overlying the upper aquifer affect movement of the contaminants from the leaky drums?

7) Explain what is happening in well GB2 and how this might affect movement of any contaminants present in the top aquifer.

8) Is bedrock observed in all the wells? What can you say about the location of bedrock where it is not observed?

9) Do you see any lenses—small units of different material that are not forming a layer across the section?

c) Constructing Groundwater Head Maps

This section takes the first step in predicting the direction of contaminant movement from the recycling plant by making maps of groundwater heads. **Two groundwater head maps (also called potentiometric surface maps) are needed, one for each of the aquifers identified in the cross section.**

Steps to facilitate drawing groundwater head maps for this site

1) On the map indicating where shallow-zone water level data are available, label each well with the water level elevation and contour the groundwater heads. The confining layer above the upper aquifer is 5 ft or less in places, so the stream channels in this area likely cut through the confining layer. In other words, assume the stream is connected to the upper aquifer and use the rule of V's for contouring near the streams. Assuming that the permeability of the material is isotropic, draw some flow arrows on the map.

2) Repeat step one for the deep wells.

Water Levels in Shallow Wells on April 8, 1990

Well	Water-level elevation
131	556.40
133	557.37
134	558.55
135	557.50
136	558.04
137	559.01
138	557.79
141	558.79
142	560.18
144	563.67
146	560.31
147	561.15
200	570.11
201	561.75
202A	559.80
203A	560.80
204A	559.78
205A	559.82
206A	559.16
207A	558.46
208A	558.43
209A	559.08
210A	558.72
211A	557.04
212A	556.78
213A	559.41
305A	557.73
306A	556.54
308A	555.43
A	557.92
B	554.83
F	554.22
G	554.77
M	555.03
N	557.10

Water Levels in Deep Wells on April 8, 1990

Well	Water-level elevation
132	556.80
140	556.65
145	556.49
220	551.59
221	550.69
222	551.15
223	550.82
224	556.32
225	556.64
226	556.91
227	555.34
308D	555.43
355	556.62

Gradient is change in head over distance (Section 2.1). It is important to use contours to determine the head difference and the map scale to determine distance along a path line perpendicular to groundwater head contour lines. Individual wells should not be used to calculate the gradient because the wells are not necessarily lined up with the groundwater gradient direction. Using the contours allows you to follow the groundwater head gradient direction. For example, from the completed shallow aquifer contour map) the gradient along the flow line south of the recycling plant the gradient is $(6\ ft)/(500\ ft) = 0.012$. When calculating the average linear velocity from Darcy's Law, you are finding the center of the plume based on average velocity, not the leading edge of the plume.

Questions about the Groundwater Head Maps

1) What is the groundwater flow direction in the shallow aquifer?
2) What is the groundwater flow direction in the deep aquifer? How does it differ from the shallow aquifer? Which aquifer has higher heads in general?
3) How do the groundwater heads in the two aquifers compare in the area where the confining zone pinches out? How do the flow directions compare in that area?
4) Could the deep aquifer become contaminated? What does the gradient between the two aquifers tell you about potential for contamination? Answer the question for both where a confining layer is present and where it pinches out.
5) Given the groundwater flow directions, what features are threatened by a plume released from the recycling plant (for example, streams, ditches)?
6) Using the map of the shallow aquifer, calculate the gradient between the recycling plant and East–West Creek. Next calculate the gradient between East–West Creek and GB-2. Comment on how much they differ.
7) If the hydraulic conductivity is 6.5 ft/day and the effective porosity is 0.2, what would be the average linear velocity between the recycling plant and East–West Creek? What is the average linear velocity between East–West Creek and GB-2?
8) Using these two average linear velocities, calculate the travel time of the center of the plume (not the leading edge) between the recycling plant and GB-2. That is, find the distance between each set of points and use the appropriate velocity to calculate the travel times. Then add the two travel times together. Do you think that this is enough time to design a remediation plan to prevent contamination of the deep aquifer? What factors might shorten the travel time? What might lengthen the travel time?

Click for solution to Exercise 14↴

Return to where text linked to Exercise 14⮥

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8 Exercise Solutions

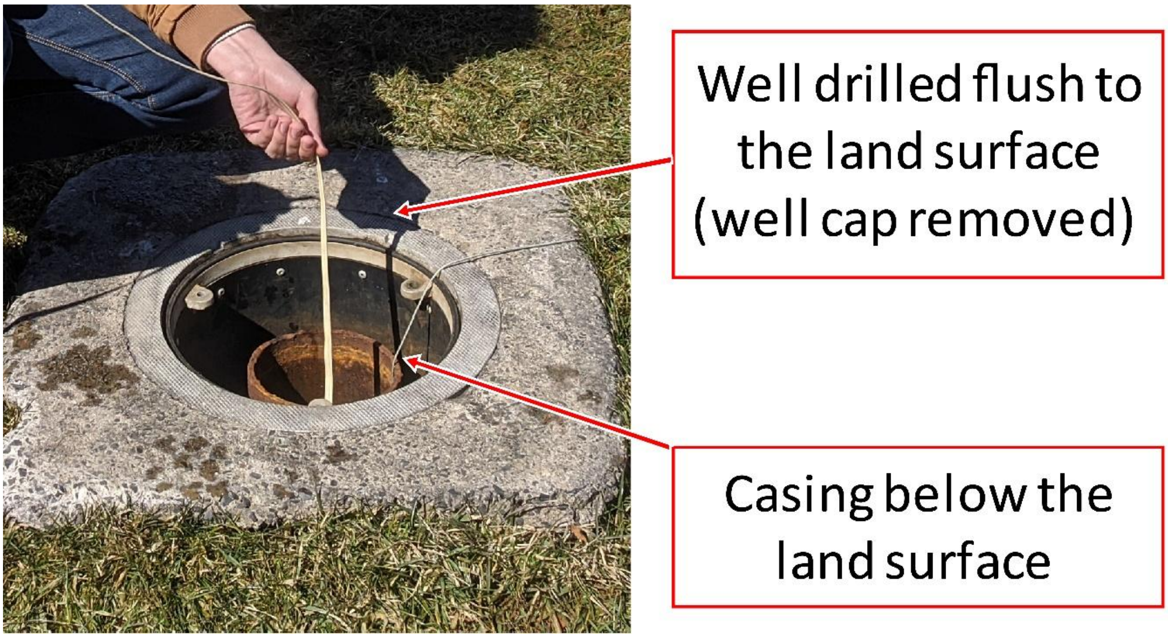
Solution Exercise 1

A spreadsheet titled "UsingGroundwaterHeadMaps-Exercise-1and2.xlsx" that provides these data in a table that you can use for developing your answers to Exercise 1 and 2 is provided for download on the book page↗.

a) First, the casing stick up or depth is converted to meters. Then the formula shown in Figure 2 is used to calculate the head:

Land surface elevation + casing stick up or depth – depth to water = head

b) The negative casing measurement indicates a casing that is below the land surface. To avoid a casing stick up that can interfere with mowing, driving, or walking, wells are sometimes "flush mounted" or flush with the land surface. Flush mounted wells are also less susceptible to vandalism.



Well ID	Land surface elevation (m)	Casing stick-up or height, units vary	Casing stick-up or height (m)	Depth to water (m)	Head (m)
MW1	125	0.3 m	0.3	21.6	103.7
MW2	48	-4 inches	-0.10	12.5	35.4
MW3	327	1.25 ft	0.38	62.1	265.3

Return to Exercise 1↑

Return to where text linked to Exercise 1↑

Solution Exercise 2

A spreadsheet titled "UsingGroundwaterHeadMaps-Exercise-1and2.xlsx" that provides these data in a table that you can use for developing your answers to Exercise 1 and 2 is provided for download on the book page↗.

a) The open interval is calculated in feet and converted to meters. The depth to water from exercise 1 is inserted in the table.

Well ID	Depth of well (ft)	Depth of casing (ft)	Open interval (ft)	Casing Depth (m)	Depth to water from Exercise 1 (m)
MW1	85	80	5	24.4	21.6
MW2	60	50	10	15.2	12.5
MW3	328	100	228	30.5	62.1

b) MW1 and MW2 have short, relatively shallow open intervals and are likely screened. MW3 has a long open interval and is likely an open borehole because that would be a lot of well screen and rather expensive.

c) MW1 and MW2 have their water level within the casing, but MW3 has the water level within the open interval as indicated by the depth of the casing being less than the depth to water.

Return to Exercise 2↥

Return to where text linked to Exercise 2↥

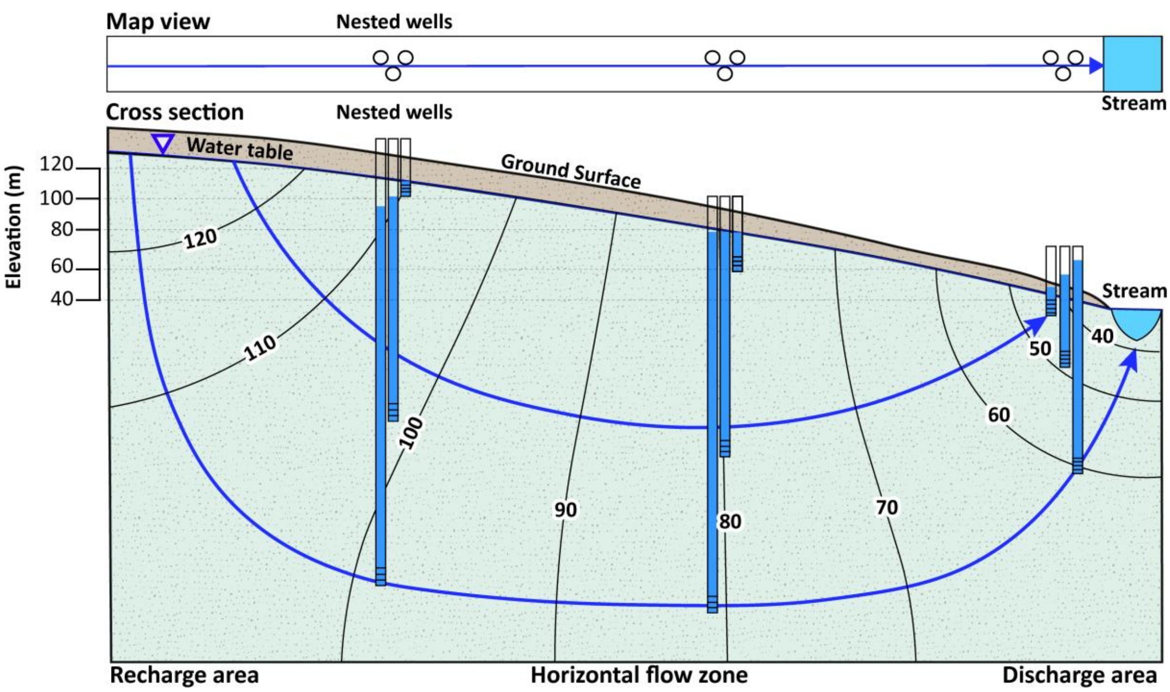
Solution Exercise 3

Water levels in the wells are shown using blue fill in the image below.

In the recharge area, the shallowest well has the highest head, indicating downward flow.

In the horizontal flow zone, the heads are essentially equal at all depths, indicating horizontal flow. The water levels in wells within the horizontal flow zone, can be used for drawing a plan view map.

In the discharge area, the deepest well has the highest head, indicating upward flow. Water levels in the discharge-area wells that are screened at depth rise above the ground surface indicating upward flow. Groundwater discharges to the stream where it then flows downstream as surface water. Groundwater also discharges from the system via transpiration by plants along the stream so it is not observable as flow at the surface, but might be discerned by noticing the type and density of vegetation along the stream relative to the uplands.



Return to Exercise 3↥

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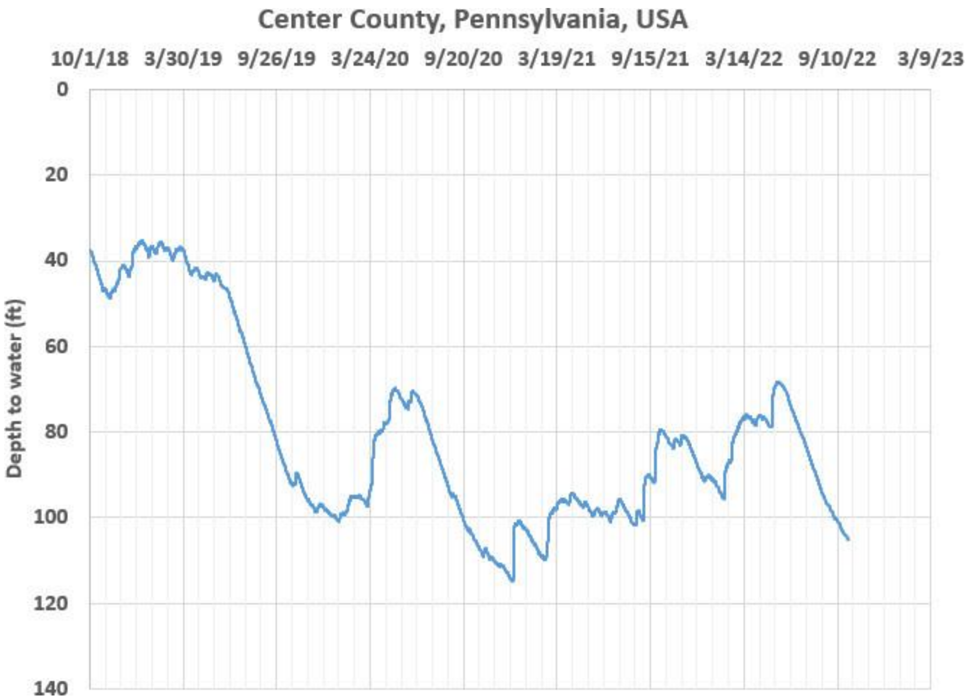
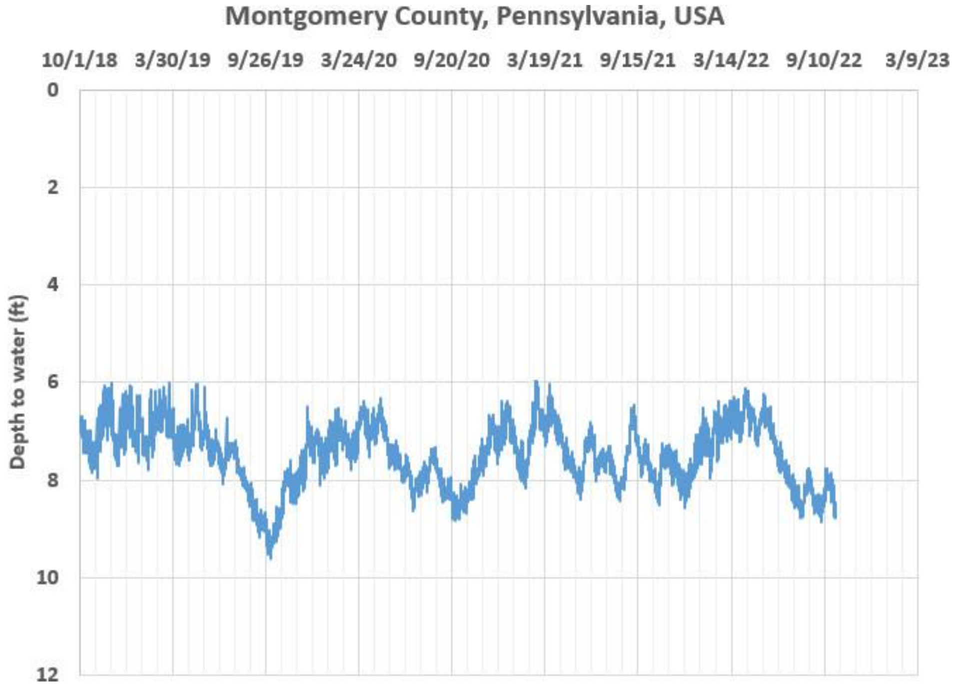
Solution Exercise 4

Worksheets showing the solution are provided in the MS-Excel spreadsheet (UsingGroundwaterHeadMaps-Exercise-4-Solution.xlsx) that can be downloaded from the book page↗.

a) The data for each well are shown below on a graph using a reverse y-axis.





b) The average monthly water levels for each October and July in both wells are shown in the tables below along with the difference between the October and July levels.

c) The average annual water level for each water year that has complete data in both wells are shown in the tables below.

Center County well data summary of depth to water in feet						
Water Year	**October* Average**	**July Average**	**Difference Oct to July**	**Water Year**	**Average 1 Oct to 30 Sep**	**Difference from Previous Year**
2019	42.61	55.60	-12.98	**2019**	47.86	
2020	89.28	79.60	9.68	**2020**	88.55	40.68
2021	106.09	97.75	8.35	**2021**	94.86	6.32
2022	81.38	85.08	-3.71	**2022**	84.38	-10.49
			Average Seasonal Variation (Abs Value)			**Average Annual Variation (Abs Value)**
All years			8.68	**All years**		19.16
Without 2019			7.25	**Without 2019**		8.04
			Seasonal Range Oct, July			**Annual Range**
All years			63.48, 42.15	**All years**		47.00
Without 2019			24.72, 18.15	**Without 2019**		10.49

Montgomery County well data summary of depth to water in feet						
Water Year	**October* Average**	**July Average**	**Difference Oct to July**	**Water Year**	**Average 1 Oct to 30 Sep**	**Difference from Previous Year**
2019	7.29	7.47	-0.18	**2019**	7.36	
2020	8.94	8.07	0.87	**2020**	7.66	0.30
2021	8.35	7.61	0.75	**2021**	7.42	-0.25
2022	7.89	8.27	-0.38	**2022**	7.53	0.12
			Average Seasonal Variation (Abs Value)			**Average Annual Variation (Abs Value)**
All years			0.54	**All years**		0.22
Without 2019			0.67	**Without 2019**		0.18
			Seasonal Range Oct, July			**Annual Range**
All years			1.65, 0.80	**All years**		0.30
Without 2019			1.05, 0.66	**Without 2019**		0.25

*October monthly average is calculated based on the previous calendar year (i.e., 2018 for water year 2019).

d) The range of values includes the following.

The range in depth to water in the Center County well is 80 ft because it varies from 35 to 115 ft. The greatest depth to water is typically in the fall or winter.

The range in depth to water in the Montgomery County well is 3.6 ft because it varies from 6 to 9.6 ft. The greatest depth to water is generally near the start of the water year late summer or fall.

e) The seasonal or annual variation is somewhat dependent on the years considered.

The depth to water was much less in 2019 than in other years in the Center County well suggesting a wet period leading into 2019 and this is also true, albeit to a lesser extent, in the Montgomery County well. The average depth to water for 2019 was only 47.86 ft compared to 84 to 95 ft in the other years for the Center County well.

In the Center County well, there is more seasonal variation than annual variation when comparing both average values and the range of values. Generally, the same is true for the Montgomery County well, except there is no difference in the seasonal range for 2020 and 2021. This is a very short period of record for drawing such conclusions because it not only includes the unusually wet year in 2019 but also includes the unusual situation in 2021 for which the water levels are deeper in July than in October.

f) The answers to (b) through (e) are generally the same for each well. There was significantly less variability in the Montgomery County well, but the trends were similar. Again, the period of record is too short to draw broad conclusions.

g) This information could be used when selecting data for a plan-view, groundwater head map. Where possible, it is important to obtain water level data for the same year and the same month. A multi-year record can be used to understand uncertainty in water levels when using data from different months or different years. This uncertainty can suggest data points that might need to be omitted from a data set or given less weight for interpreting a head map.

Return to Exercise 4↥

Return to where text linked to Exercise 4↥

Solution Exercise 5

a) The bay is connected to the ocean, so it is at a head equal to average sea level which is the datum of zero.

b) Head (water level) values for the wells in the red boxes are estimated by interpolating between contour lines:

 N9078: ~50.3

 N9666: ~34.2

 N1183: ~29.7

 N9470: ~11.9

 N1186: ~5.6 (using the coast as a contour equal to zero).

c) Head changes from 1988 to 1990 are listed below. Head changes are larger inland because average sea level is constant.

 N9078: ~50.3 to 55.64, head rose ~5.34 ft

 N9666: ~34.2 to 40.08, head rose ~5.88 ft

 N1183: ~29.7 – no data available for 1990

 N9470: ~11.9 to 15.44, head rose ~3.54 ft

 N1186: ~5.6 to 6.59, head rose ~0.99

 The well between the 20 and 25 ft contours increased in head by almost 5 ft (4.93). The well near the 10 ft contour increased 2.13 ft.

d) The overall pattern in the autumn of 1988 and 1990 is similar but the contour lines in the vicinity of East Meadow Brook curve slightly downstream in 1988 suggesting flow outward from the stream to the groundwater system, and the contour lines curve slightly upstream in 1990 suggesting flow toward the stream from the groundwater system.

Return to Exercise 5↥

Return to where text linked to Exercise 5↥

Solution Exercise 6

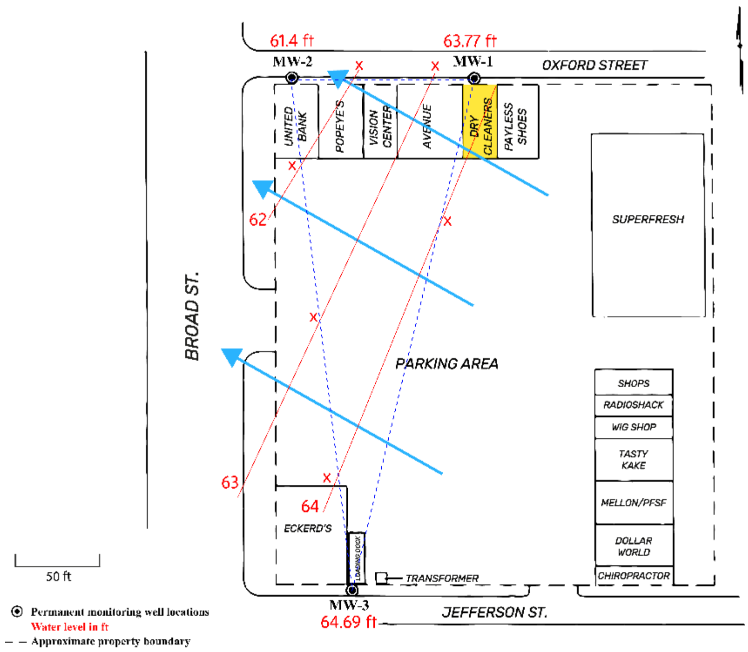
a) With three data points, straight contour lines are the only reasonable option because there is no information to suggest a bend in the lines and it is best to choose the simplest solution until additional data suggest otherwise. The questions posed do not require a precise answer, so visual estimation of contour locations between the monitoring wells is sufficient. For completeness, exact interpolation of the contour locations is provided in a spreadsheet available for download on the book page.
Approximate method: As illustrated in the image show here, dashed lines are drawn between the wells, then visual interpolation between the values at the two wells is used to place X's on the dashed lines for the water level values of 62, 63, and 64. The straight contour lines are drawn by connecting points with the same value.
Exact method: A spreadsheet titled "UsingGroundwaterHeadMaps-Exercise-6-Solution.xlsx" that illustrates how to calculate the contour locations is provided for download on the book page↗.

b) The contour lines are labeled on the map shown below.

c) Arrows indicate the flow direction.

d) MW1 and MW2 are both susceptible to dry cleaner fluid contamination. MW2 is not as close, but it is still along a flow path that contaminants will follow.

e) MW3 is upgradient, so even though it is in on the edge of the shopping plaza, it would not have fluids from the Dry Cleaners. However, it may have contamination from other businesses in the area. There is a transformer near MW3, and if it leaks it could be a source of contamination.



Return to Exercise 6↥

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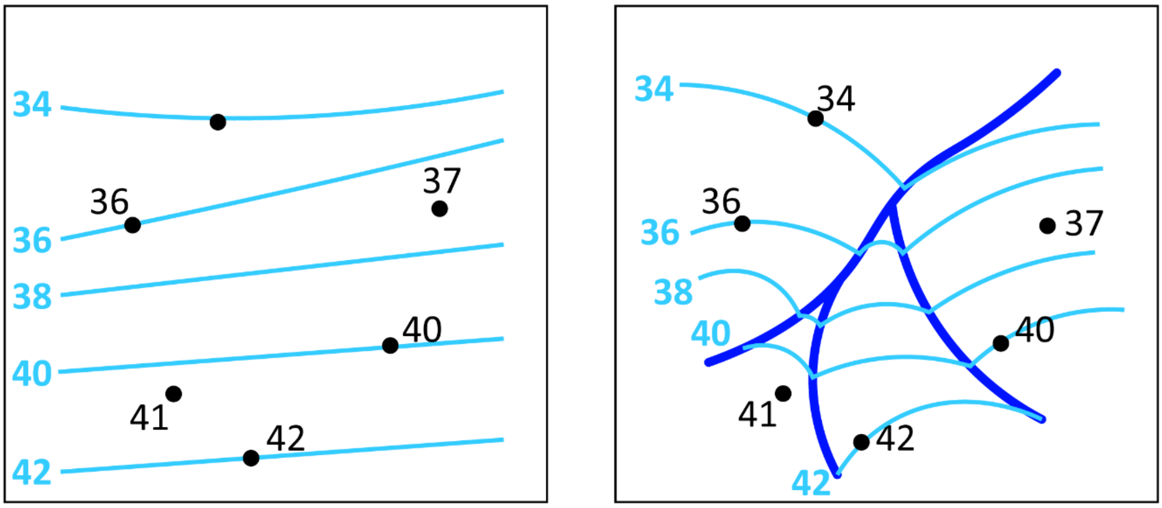
Solution Exercise 7

On the left, groundwater is much deeper than the stream and thus does not discharge to the stream (i.e., the stream is perched). The resulting contours show a general northward flow direction with variations caused by changes in subsurface material or influences on flow that are not available in the figure.

On the right, connection of the groundwater and surface water allows one to use the elevation where the stream intersects surface contours as data points for groundwater head. The V's in the groundwater head contour lines indicate groundwater discharges to the stream.



[Return to Exercise 7](#)↑

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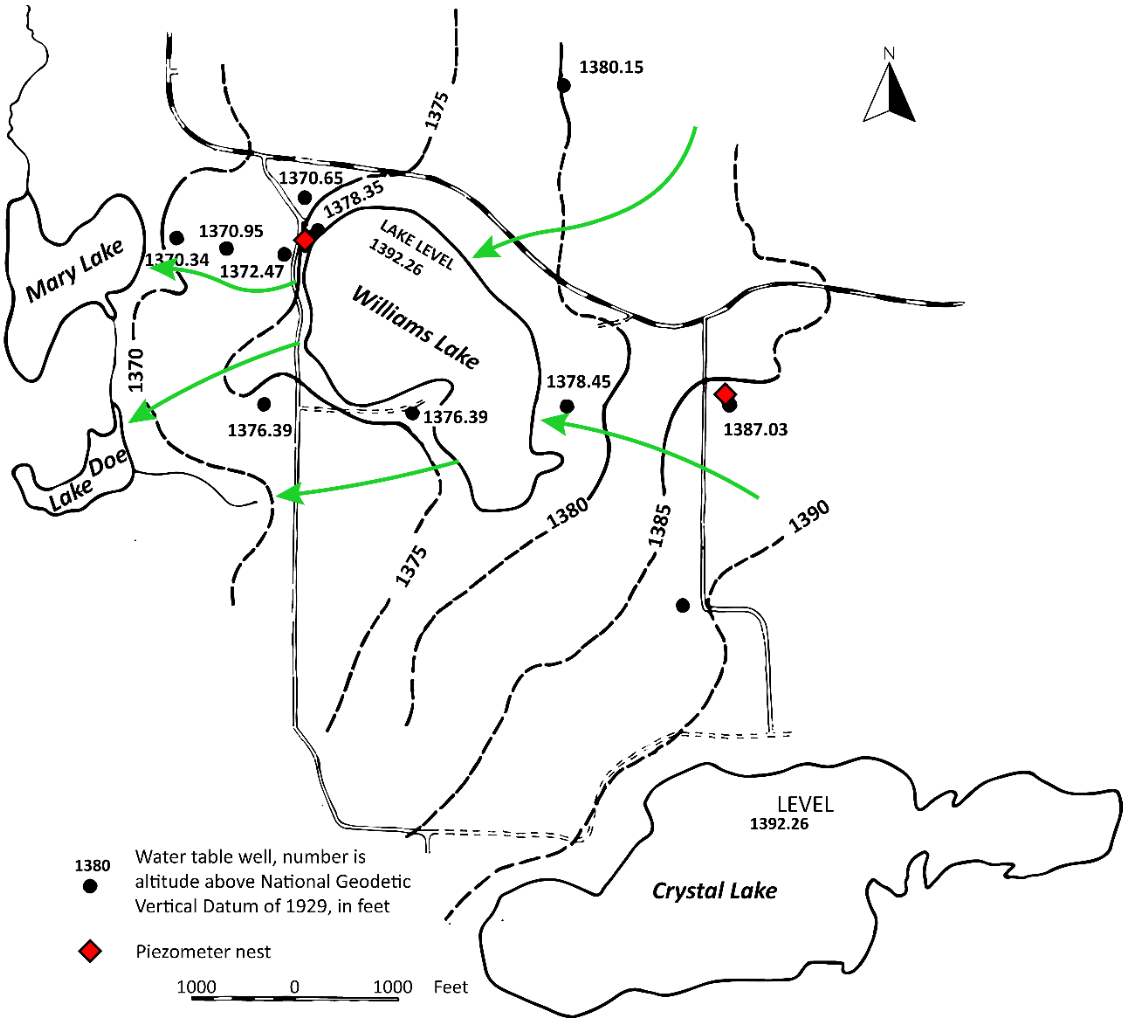
Solution Exercise 8



Lake Williams is both a recharge and a discharge area! Groundwater is discharging to the lake from the east end and lake water is recharging to groundwater in the west as illustrated by the arrows drawn perpendicular to the lines of equal head.

Return to Exercise 8↥

Return to where text linked to Exercise 8↥

Solution Exercise 9

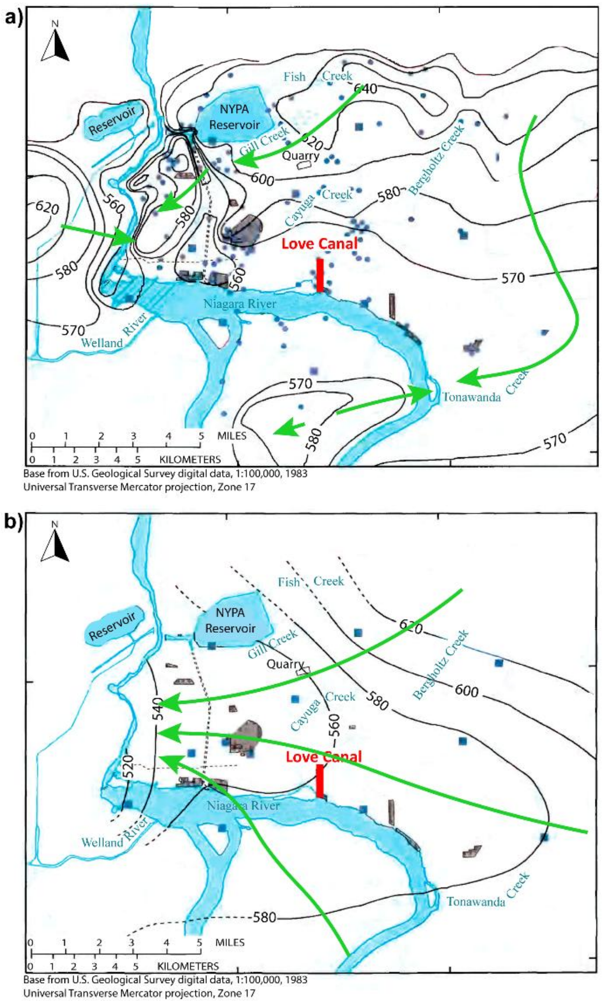
a) The highest and lowest head contours mapped in the overburden (map a) are 640 ft and 560 ft.

b) The highest and lowest head contours mapped in the lower dolomite aquifer (map b) are 620 ft and 520 ft.

c) There is potential for downward groundwater flow from the upper to lower aquifer based on the direction of the head gradient because, in most areas of the maps, the heads are higher in the upper aquifer relative to heads in the lower aquifer.

d) The head contour closest to Love Canal in the overburden is about 565 ft because there are contours of 570 ft on either side, with a dip in between. For the lower dolomite aquifer, the 560-contour crosses through the canal. Thus, the head levels are similar given the scale of the map, but even in the vicinity of the canal, there is likely to be downward groundwater flow.

e) A few flow lines from the high points to the low points are drawn on each map and shown below.



f) On the dolomite head map (b), heads are high in the east and low near the central segment of the river. Groundwater flows from the east to the central segment of the river.

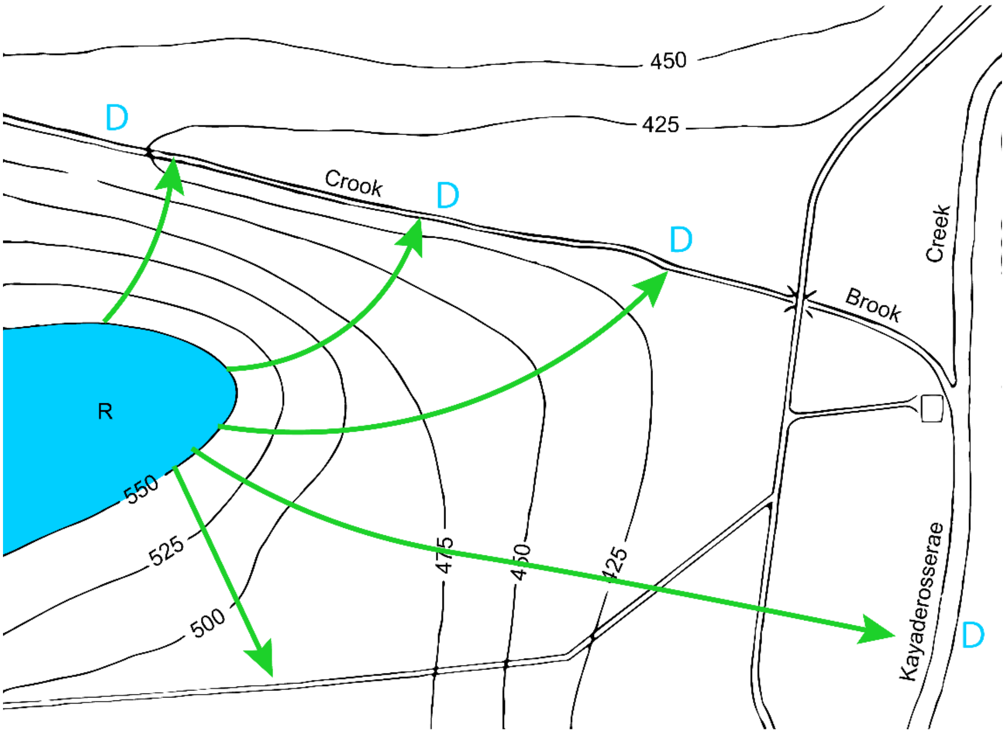
g) On the overburden map (a), heads are high in the northeast corner and also in the west. Groundwater flows from these areas toward the river. The flow pattern in the overburden is more complex than in the dolomite, with a slightly more southward component and some opposing flow toward the east in the western part of the map.

Return to Exercise 9⮥

Return to where text linked to Exercise 9⮥

Solution Exercise 10

Flow lines are drawn perpendicular to lines of equal groundwater head. The radiating flow lines indicate a recharge area. The outline is illustrative and not a precise definition of the limits of where recharge occurs. The brook and creek are discharge locations.



[Return to Exercise 10](#)↥

[Return to where text linked to Exercise 10](#)↥

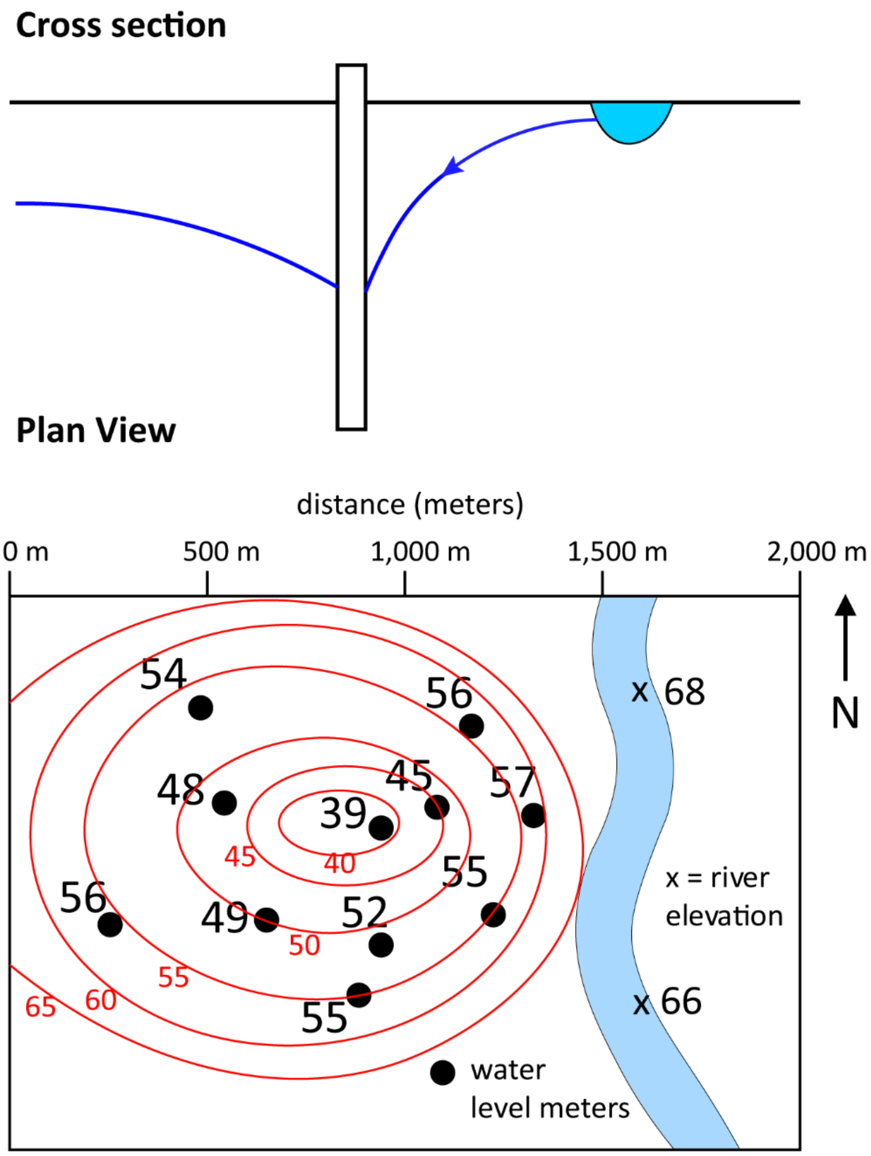
Solution Exercise 11

a) Contours are shown in plan view and in cross section to indicate the relationship with the stream.

b) The pumping well is a bit west of the 39-m head measurement.

c) Heads are higher between the pumping well and the stream.

d) The contours are steeper between the pumping well and the stream because there is enough surface water flow in the stream that the stream elevation does not change significantly when the well is pumped, and water flows from the stream into the groundwater system, keeping the head high on that side of the well. The cone of depression may extend to the east beyond the stream, but head data are not available on the far side of the stream to investigate this.

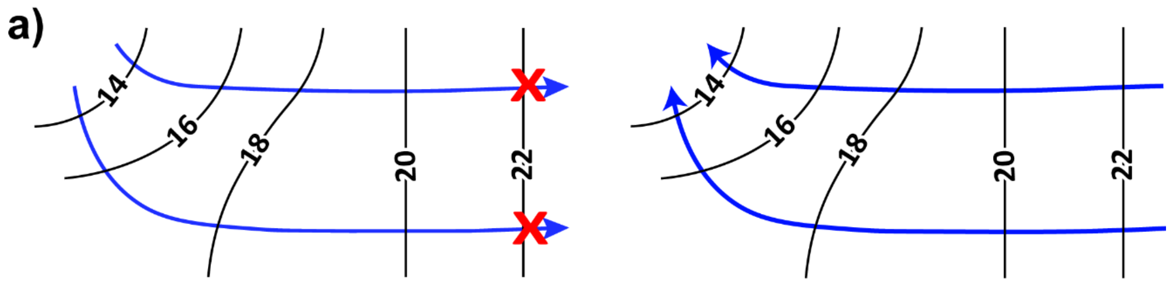


[Return to Exercise 11](#)

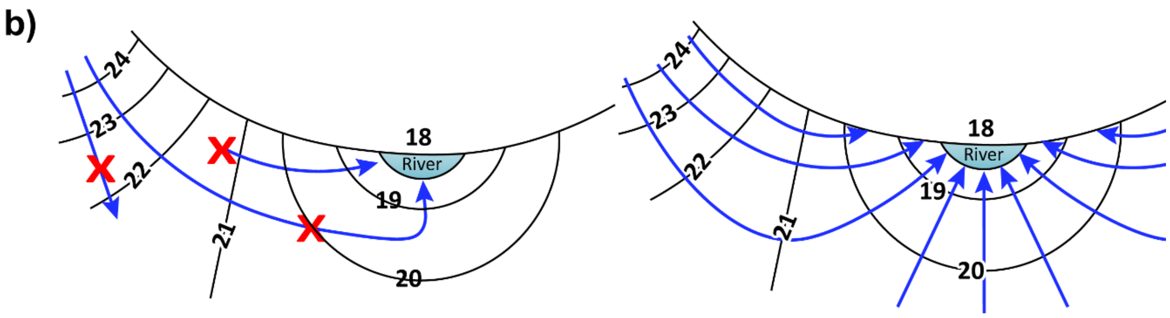
[Return to where text linked to Exercise 11](#)

Solution Exercise 12

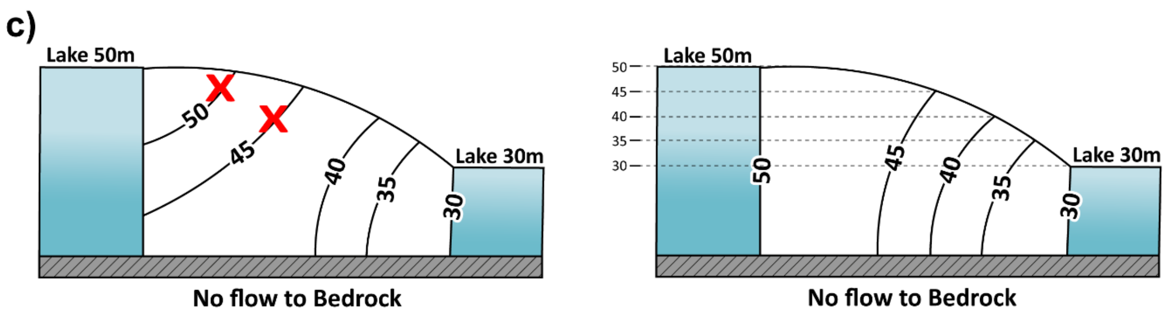
a) Left, incorrect: The flow arrows point in the wrong direction. Right, corrected: Arrows reversed and placed on opposite end of flow lines.



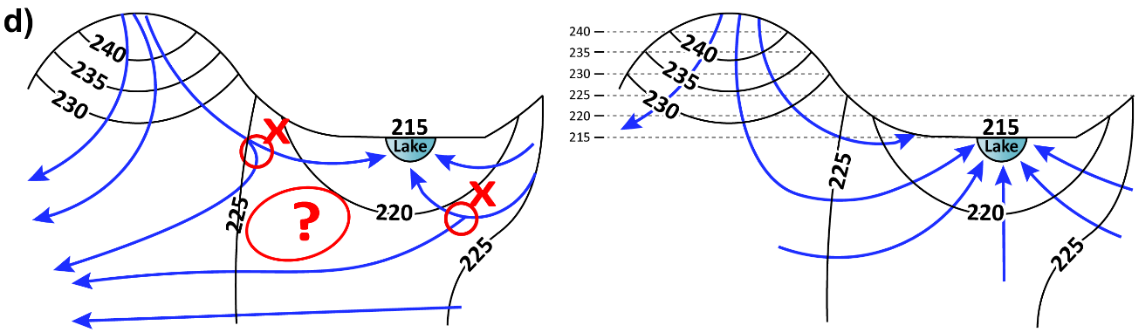
b) Left, incorrect: Flow lines are not perpendicular to head contour lines. Some of the flow lines start or stop in the middle of the map. The flow line near the 19 contour label changes direction too abruptly. Right, corrected: The flow lines are continuous from upgradient to the river discharge area. They are all perpendicular to contours.



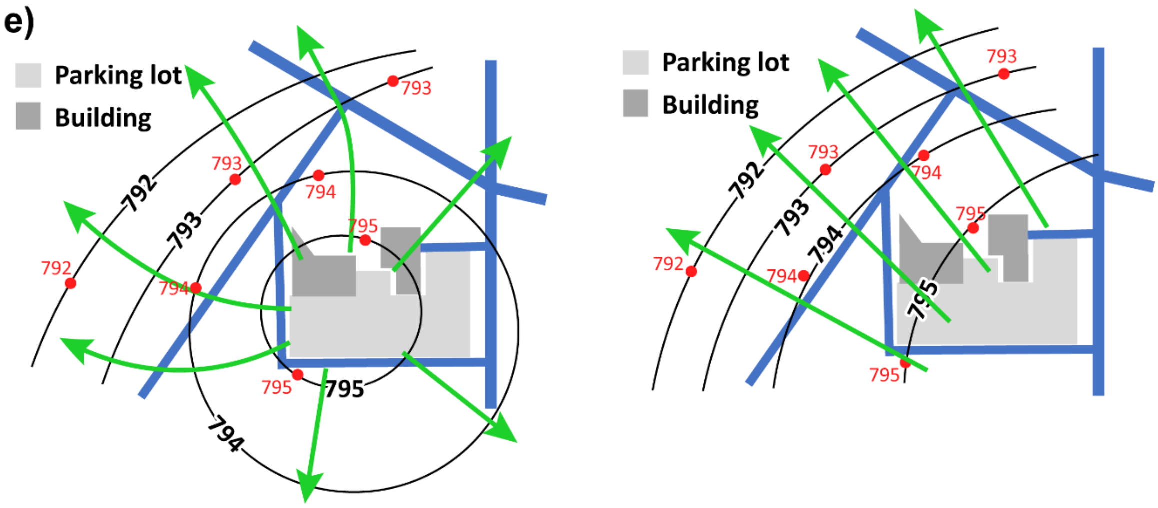
c) Left, incorrect: Head in the lake is constant with depth at 50, yet the 45 and 50 contours intersect the lake. Right, corrected: The 50 contour is at and parallel to the lake.



d) Left, incorrect: There are two places that the flow lines split. There is a stagnation zone in the middle that should have some flow lines. Right, corrected: More flow lines are included to get rid of the splitting. The contours and flow lines extend into the former stagnation zone.



e) Left, incorrect: The map shows groundwater recharge occurring through a parking lot. That does not make sense because pavement is not very permeable and water tends to run off. Right, corrected: Rather than representing a mound under the parking lot, the data are instead interpreted as representing flow under the parking lot from the southeast. The flow lines are drawn perpendicular to the contour lines.

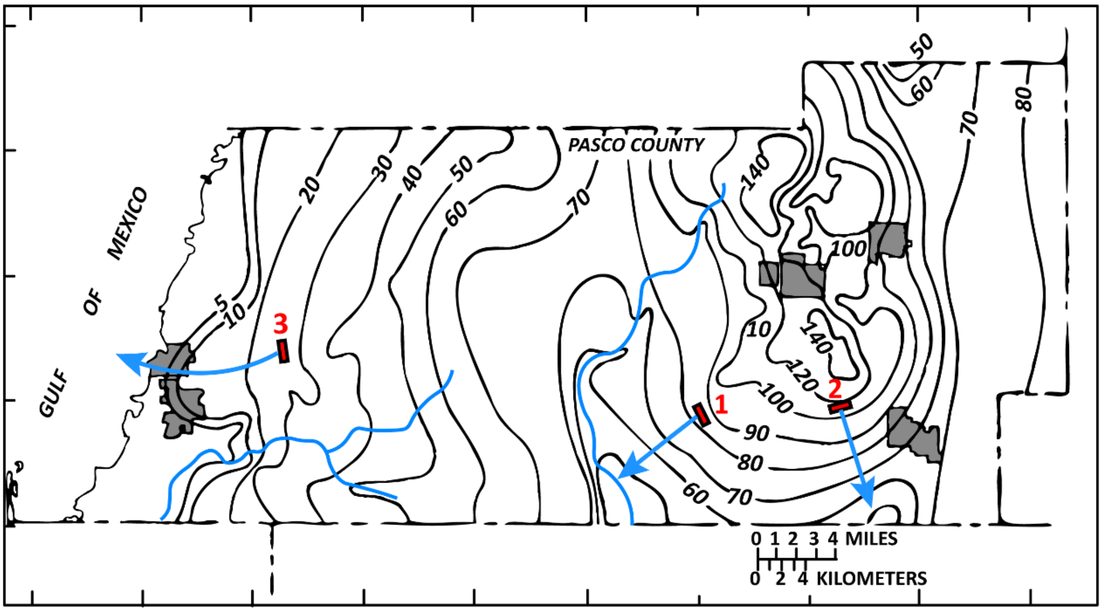


Return to Exercise 12

Return to where text linked to Exercise 12

Solution Exercise 13

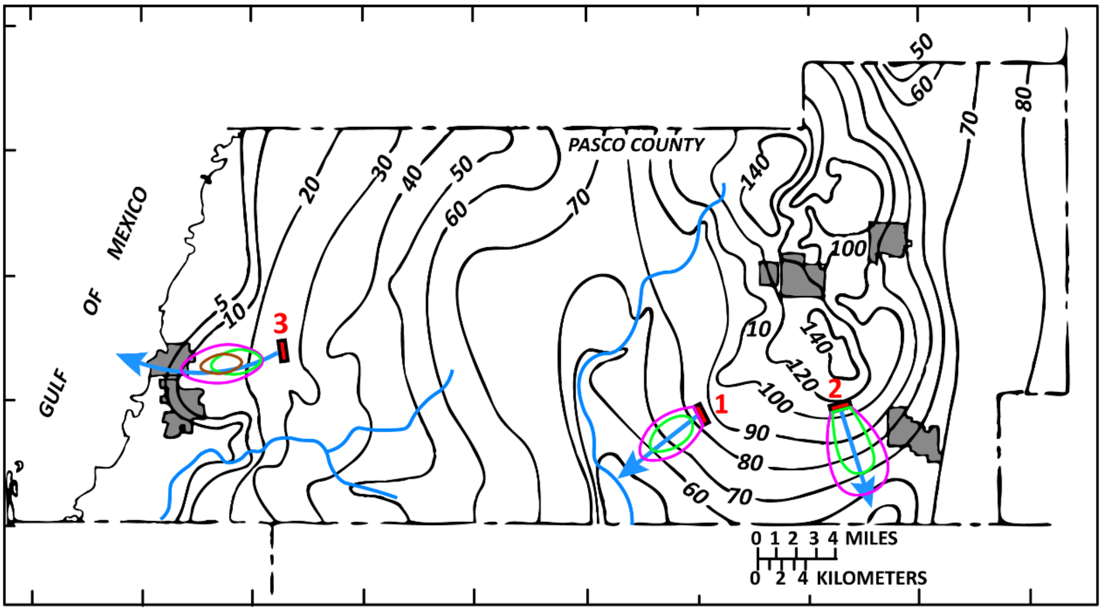
a) Flow lines from each source area are drawn in blue on the image below.



EXPLANATION

—— 20 —— LINE OF EQUAL WATER TABLE ELEVATION ABOVE SEA LEVEL IN SEPTEMBER 1984
CONTOUR INTERVAL 5 AND 10 FEET

b) Plumes reflecting the flow direction as well as the nature of the source and the dispersivity of the system are drawn on the image below.



EXPLANATION

—— 20 —— LINE OF EQUAL WATER TABLE ELEVATION ABOVE SEA LEVEL IN SEPTEMBER 1984
CONTOUR INTERVAL 5 AND 10 FEET

SOURCE AREA 1: The continuous source plume is the magenta line; the spill plume is the green line that is disconnected from the red source area. They both have similar dispersion, but the spill plume is smaller because less contaminant mass is in the plume because a spill introduces mass for a finite period of time while a continuous source introduces mass indefinitely. The stream on the map is likely to receive contamination from these plumes.

SOURCE AREA 2: The source is identical for each of these plumes but the magenta line shows the plume in an aquifer with large dispersivity than the green line. At the time reflected by this map the plume has not reached the developed area, but if dispersion was larger, contamination could reach the developed area by this time. As the sources continue to introduce contaminant indefinitely the plume will eventually spread to reach the developed area unless there is natural decay of the contaminants. If the contaminant is volatile, the shallow subsurface may be contaminated with off-gases. If there are water supply wells for the development in the vicinity, water samples should be collected and analyzed for the presence of contaminants.

SOURCE AREA 3: The magenta plume is not retarded and has spread more and traveled further than the other plumes. The green plume is slowed by sorption, showing a contracted version of the magenta plume shape and shorter travel distance. The brown plume has the same shape and the same center of mass as the magenta plume which is not retarded but the brown plume is smaller in all dimensions because some of the contaminant has decayed. The plumes have reached or will reach the developed area, creating the same concerns listed above. The plume could reach the gulf, and depending on the contaminant could affect aquatic life at the shore.

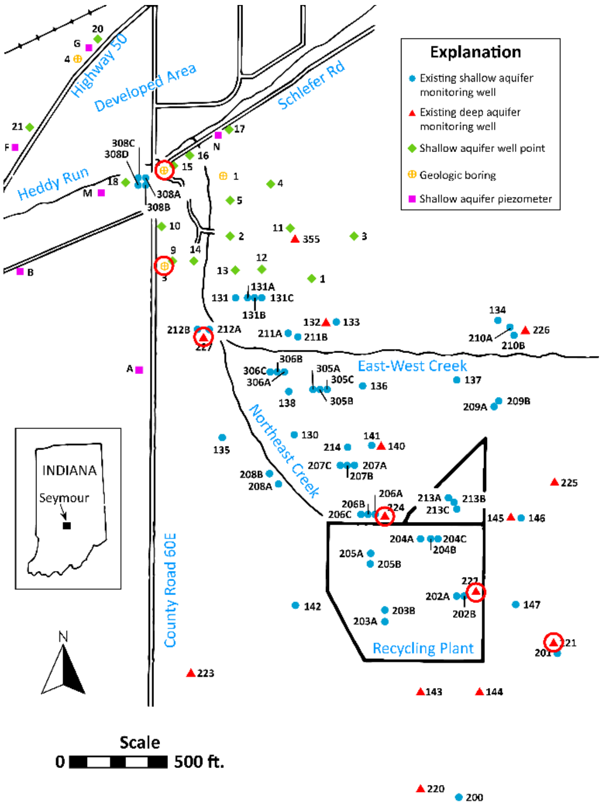
Return to Exercise 13⮥

Return to where text linked to Exercise 13⮥

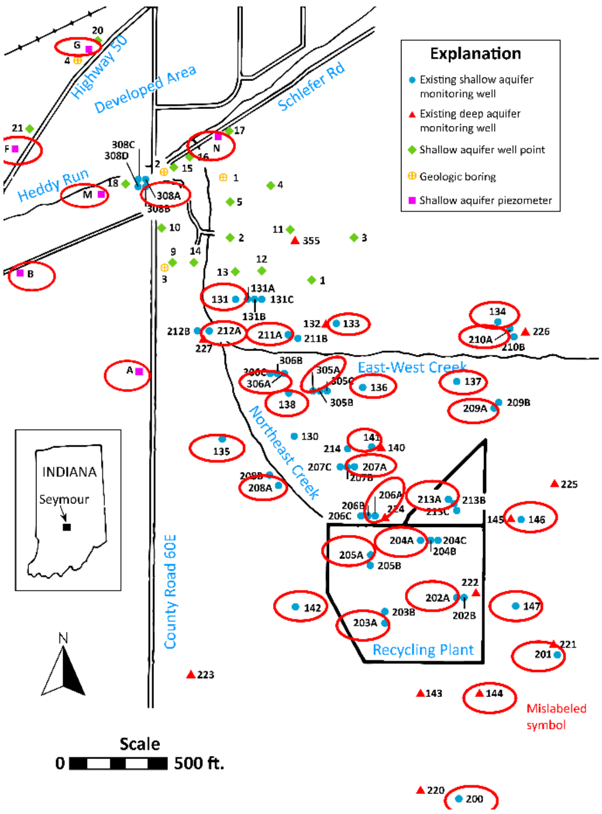
Solution Exercise 14

a) Well Location Maps

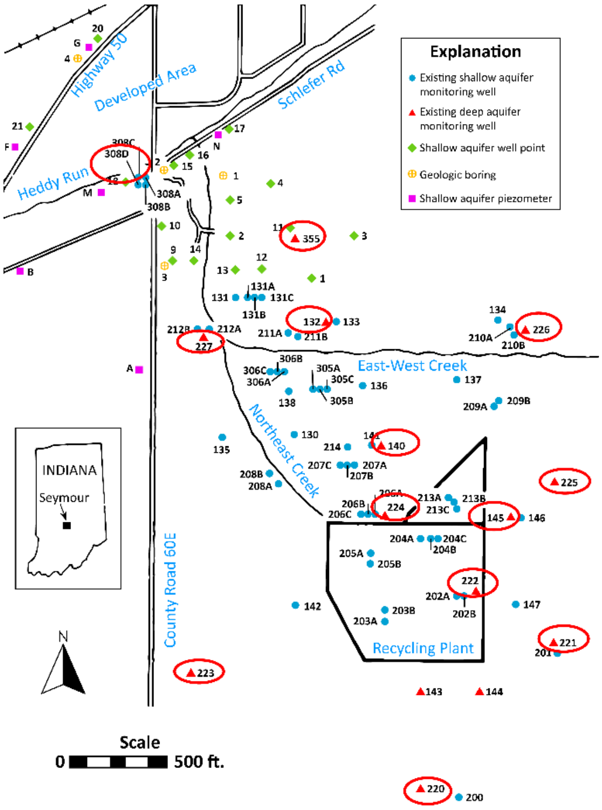
with geologic descriptions



with shallow-well water levels



with deep-well water levels

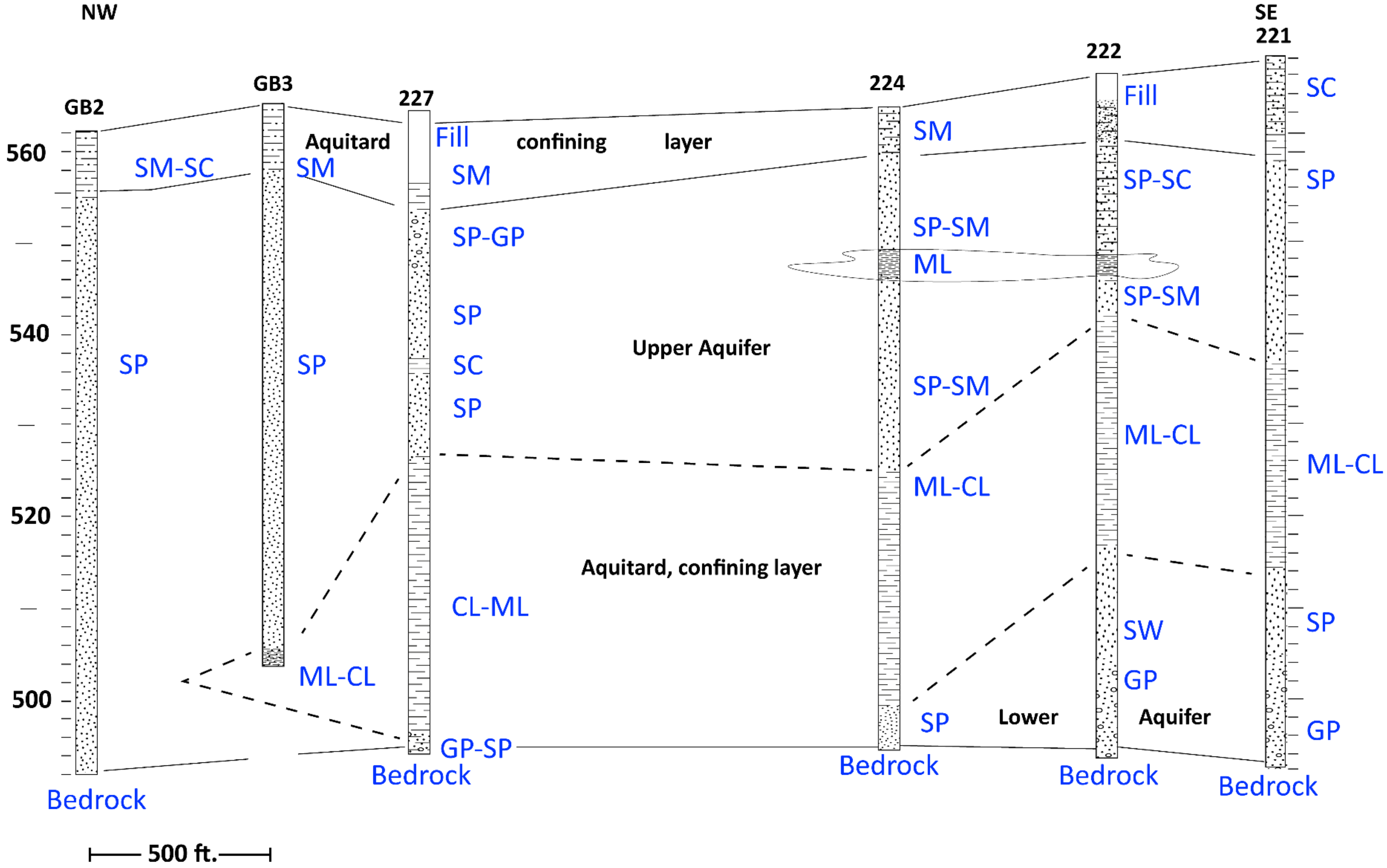


b) The Cross Section

Answers to Questions about the Unified Soil Classification System

1. *Is a unit labeled MC an aquitard or aquifer?* Silty clay is an aquitard
2. *Is a unit that has S as the first letter an aquifer or aquitard?* It depends on whether the second letter relates to sorting (P or W) or relates to grain size (C or M). If the second letter related to sorting, then the unit is a sand or an aquifer, albeit with lower permeability if it is poorly sorted (P). If the second letter relates to grain size, then S is an adjective (sandy), and the second letter determines whether it is an aquitard. If the second letter is C, it is an aquitard. If the second letter is M, it is often an aquitard but can be an aquifer if there is a lot of sand nearby.
3. *Is a unit labeled GP an aquifer or aquitard?* GP is poorly sorted gravel, which is nonetheless and aquifer.

Cross section:



Answers to Questions about the Completed Cross Section

4) *Is there one or more aquitards? Describe the unit(s) in terms lithology (grain size or rock type) and bedding. Bedding refers to the geometry and thickness of the layers.* Assuming all units are groundwater-bearing, there are three aquitards. At the base, there is a bedrock aquitard. Its thickness is not shown, but it extends the full width of the cross section. The fine-grained unit of silt and clay is also an aquitard. It is about 20 ft thick on the SE side of the section, thickening to 25 ft in well 227. Beyond well 227, this unit decreases in thickness and pinches out between GB3 and GB2. This unit is labeled as a confining layer because it lies below the saturated zone and overlies the lower aquifer. A third aquitard is shallow, and 4 to 6 ft thick along the top of the cross section. This unit is comprised of clay and sandy silt. This unit is labeled as a semi-confining layer because it depends on whether the water level is above the top of the upper aquifer, and that could potentially vary from time to time in a shallow aquifer. There are a couple of wedges of fill with unknown permeability within this shallow aquitard appearing in wells 227 and 221.

5) *Is there one or more aquifers? Describe the unit(s) in terms of lithology and bedding.* Assuming groundwater is present in the coarse-grained layers, then there is an upper aquifer of poorly sorted sand with some sandy silt and clay. There is a lens of "pure" silt crossing between wells 222 and 224, but it is not continuous. This upper aquifer is around 20–25 ft thick across most of the section but thickens to 45 ft then 50 ft in wells GB2 and GB3, respectively. Just above the bedrock is a second aquifer, comprised of poorly sorted sand and gravel. It is about 20 ft thick on the SE side, but pinches down to just a few feet in wells 224 and 227. In GB2, the upper and lower aquifer form a single unit, with no aquitard between them.

6) *How might the presence of an aquitard overlying the upper aquifer affect movement of the contaminants from the leaky drums?* The low permeability aquitard provides some protection from movement of contaminants into the upper aquifer even if the head gradient direction is downward because the transmission rate will be low.

7) *Explain what is happening in well GB2 and how this might affect movement of any contaminants present in the top aquifer.* The lower aquitard pinches out and the two aquifers are joined in GB2. Any contaminants that have migrated to GB2 have the potential to move into the lower aquifer without protection from a confining aquitard.

8) *Is bedrock observed in all the wells? What can you say about the location of bedrock where it is not observed?* Bedrock is observed in all the wells except GB3. This well was not drilled as deep as the other wells, so it is unknown where the shale layer occurs. It likely crosses beneath this well at a similar elevation to the other wells (around 496 ft.) The line for the bedrock elevation should not change when crossing through this well, although use of a dashed line is appropriate.

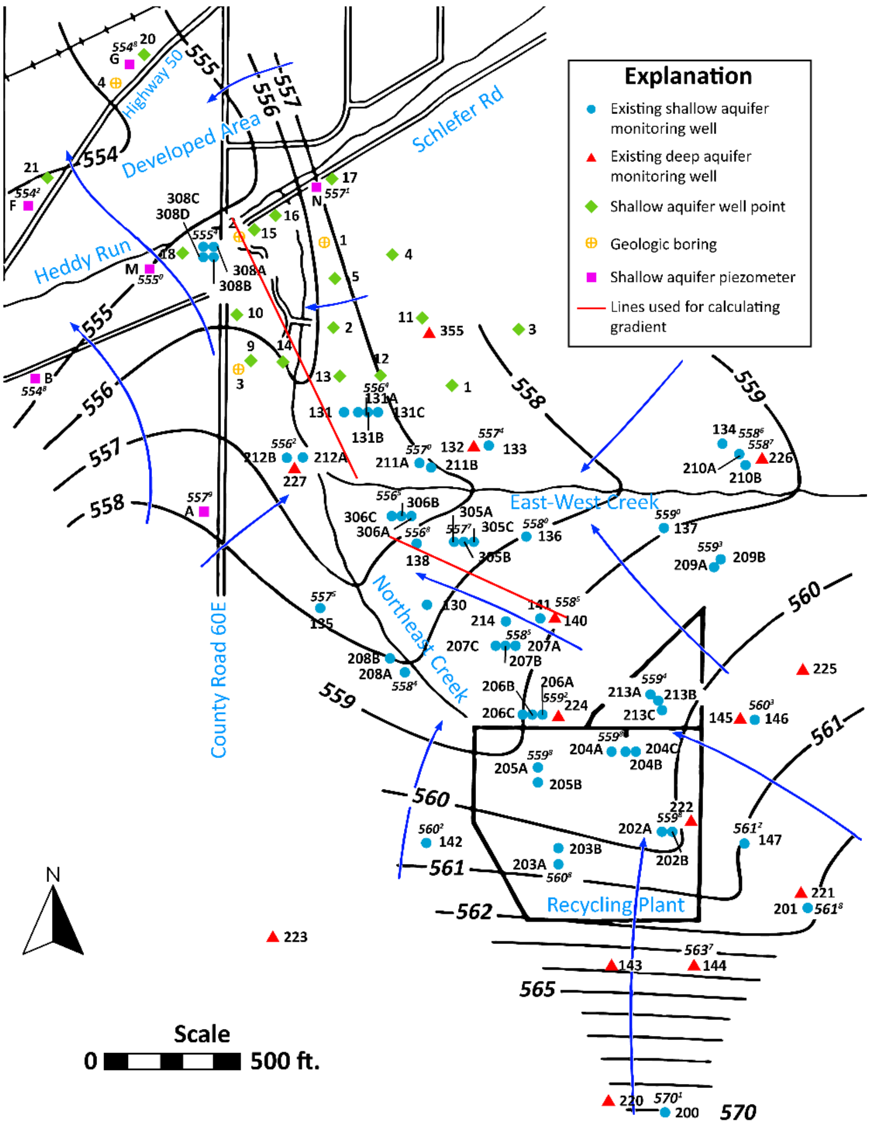
9) *Do you see any lenses – small units of different material that are not forming a layer across the section?* The most distinct lens is the 2 ft thick layer crossing between wells 224

and 222. There is another clayey sand layer within 227 and two wedges of fill material at the top of 227 and 222.

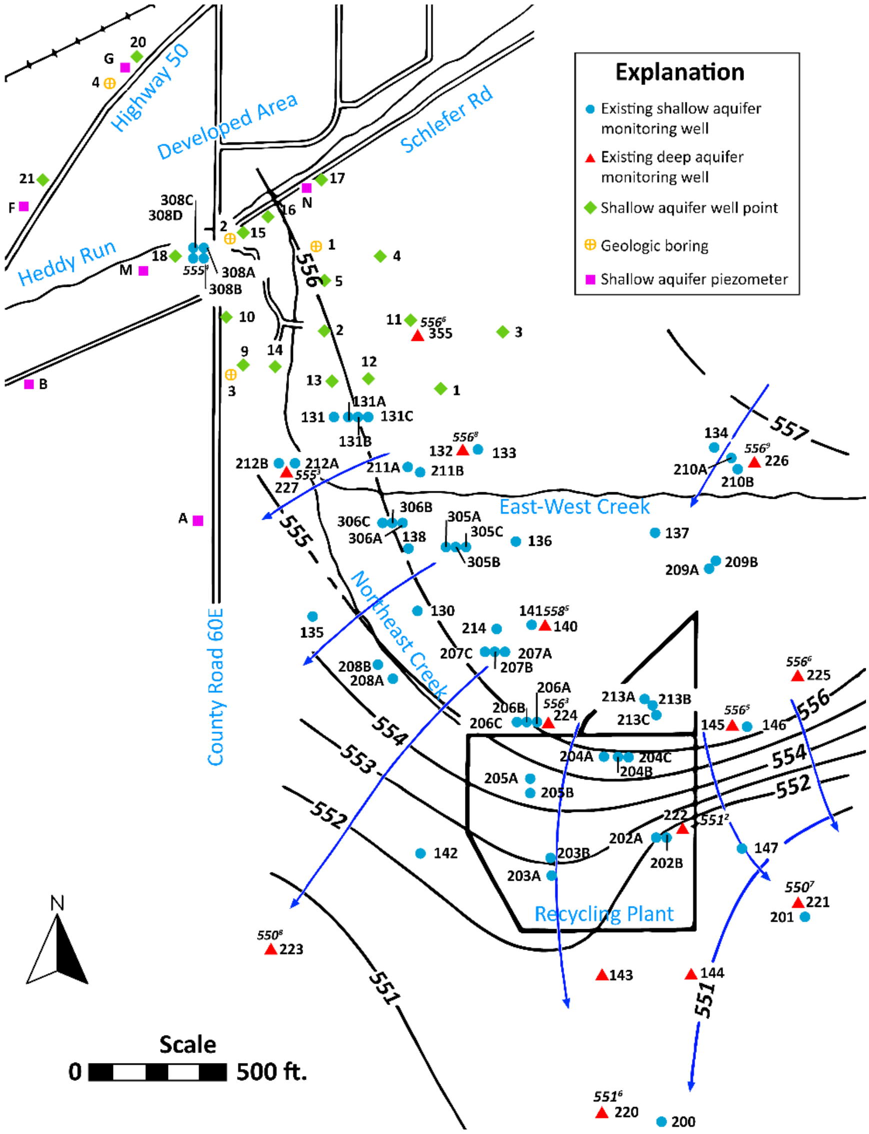
c) Groundwater Head Maps

Contour map for shallow aquifer

The confining layer thickness above the shallow aquifer is 5 ft or less in places so it is assumed that the stream channel cuts through the layer such that the stream is connected to the shallow aquifer. The available head data support this connection, so the stream elevations were included in the construction of groundwater head contours.



Contour map for deep aquifer



Answers to Questions about the Groundwater Head Maps

1. *What is the groundwater flow direction in the shallow aquifer?* In the shallow aquifer, groundwater flows in from the south, and curves northwest beneath the recycling plant, following the direction of surface drainages. The head contours V upstream. There is westerly flow north of Heddy Run and Schlefer Road.

2. *What is the groundwater flow direction in the deep aquifer? How does it differ from the shallow aquifer? Which aquifer has higher heads in general?* The groundwater flow in the deep aquifer is generally from north to south with a southwest trend on the west side of the map. In most parts of the map (to the west and to the south) the groundwater heads are lower in the deep aquifer.

3. *How do the groundwater heads in the two aquifers compare in the area where the confining zone pinches out? How do the flow directions compare in that area?* Where the confining zone pinches out between GB2 and GB3, both aquifers have head elevations around 555 and 556 ft. However, the flow directions differ. The shallow aquifer heads indicate a north groundwater flow direction with only a slight westerly trend, and the deep aquifer heads indicate a westerly flow direction. Near Northwest Creek the flow directions in the two aquifers are opposite each other (easterly and westerly).
4. *Could the deep aquifer become contaminated? What does the gradient between the two aquifers tell you about potential for contamination?* Heads are higher in the upper aquifer so the gradient is downward. In most areas, there is an aquitard that slows movement between the aquifers. However, if the contaminant plume spreads to the area where the confining zone pinches out the plume could enter the deep aquifer and then migrate to the west-southwest within the deep aquifer.
5. *Given the groundwater flow directions, what features are threatened by a plume released from the recycling plant* (for example, streams, ditches)*?* The groundwater in the shallow aquifer is moving toward the creeks. It is also moving north toward the town where there used to be groundwater supply wells.
6. *Using the map of the shallow aquifer, calculate the gradient between the recycling plant and East–West Creek. Next calculate the gradient between East-West Creek and GB-2. Comment on how much they differ.* From the recycling plant to E–W Creek, the gradient along the flow line is $(559 - 557\ ft)/(800\ ft) = 0.0025$
From E–W Creek to GB2, the gradient along the flow line (diagonal from in between the two contours by the creek, NW to the nearest contour to GB2) is $(556.6 - 555\ ft)/(1200\ ft) = 0.0013$
The contours are more widely spaced to the north and the gradient is about half the gradient closer to the plant.
7. *If the hydraulic conductivity is 6.5 ft/day and the effective porosity is 0.2, what would be the average linear velocity between the recycling plant and East–West Creek? What is the average linear velocity between East–West Creek and GB-2?*
Velocity between recycling plant and E–W Creek:
$$\left(\frac{6.5\,\frac{\text{ft}}{\text{day}}\ 0.0025}{0.2}\right) = 0.08125\ \frac{\text{ft}}{\text{day}}$$
Velocity between E–W Creek and GB2:
$$\left(\frac{6.5\,\frac{\text{ft}}{\text{day}}\ 0.0013}{0.2}\right) = 0.04225\,\frac{\text{ft}}{\text{day}}$$
8. *Using these two average linear velocities, calculate the travel time of the center of the plume (not the leading edge) between the recycling plant and GB-2. That is, find the distance between each set of points and use the appropriate velocity to calculate the travel times. Then add the two travel times together. Do you think that this is enough time to*

design a remediation plan to prevent contamination of the deep aquifer? What factors might shorten the travel time? What might lengthen the travel time?

Travel time equals distance divided by velocity.

Travel time between recycling plant and E–W Creek:

$$\frac{800 \text{ ft}}{0.08125 \frac{\text{ft}}{\text{day}}} = 9846 \text{ days} = 27 \text{ years}$$

Travel time between E-W Creek and GB2:

$$\frac{1200 \text{ ft}}{0.04225 \frac{\text{ft}}{\text{day}}} = 28{,}402 \text{ days} = 77 \text{ years}$$

$$\text{Total travel time} = 27 + 77 = 104 \text{ years.}$$

This should be enough time to develop a remediation plan that would prevent spread of contamination to the north and into the lower aquifer.

The travel time is only the average or center of the plume. The leading edge of the plume travels faster due to dispersion. If the concentration at the leading edge reaches a level of concern, then 104 years might not be enough time. If the geologic unit has a high permeability zone not mapped in the cross section, the plume could also travel faster. Factors that could lead to longer travel times are sorption and decay.

Return to Exercise 14⮥

Return to where text linked to Exercise 14⮥

9 About the Author

Laura Toran is Weeks Chair in Environmental Geology in the Earth and Environmental Science Department at Temple University in Philadelphia, Pennsylvania, USA. Dr. Toran has taught Groundwater Hydrology and Groundwater Modeling there for 28 years, where she has received awards for teaching and mentoring. Before joining the faculty at Temple University, she conducted research on hazardous waste sites at Oak Ridge National Laboratory in Tennessee for 11 years. She has served as a rotator for the Hydrology Program at the National Science Foundation, as a committee member for the National Academy of Sciences, and as an editor or associate editor of the journals Groundwater, Water Resources Research, and Hydrogeology Journal. She has authored papers on groundwater modeling, karst hydrology, hydrogeophysics, and urban hydrology.

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